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Paleomagnetism of Miocene dikes in the Shitara basin and the tectonic evolution of central Honshu, Japan

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Central Honshu, Japan, is conspicuous for a northward-convex form of zonal geologic structures. To clarify the formation of curvature of the zonal structures in the west of the convex form and further to discuss the tectonic evolution of central Honshu, we carried out a paleomagnetic study of dated (∼15 Ma) dike rocks of the Shitara basin. Samples were collected from 25 basalt dikes trending north-south with a nearly vertical intrusion surface. After stepwise alternating-field and thermal demagnetization, 24 site-mean directions were determined. Three dikes gave anomalous directions, probably resulting from instantaneous recording of a field transition or excursion. The other 21 site-means produced a mean direction, $D = 9.7^\circ$, $I = 54.5^\circ$, $\alpha_{95} = 5.2^\circ$, and a paleomagnetic pole at 82.3°N, 216.6°E, $A_{95} = 6.2^\circ$. Although the reversal test is negative at the 5% significance level, the mean direction and pole are time-averaged ones in which the secular variation is averaged out. This was confirmed by studying the angular standard deviation of virtual geomagnetic poles. We conclude that the central Honshu curvature formed when the southwest Japan arc rotated clockwise between 17 and 15 Ma in relation to the opening of the Japan Sea, associated with differential rotation of the eastern part of the arc with respect to the central part. The differential rotation probably resulted from a sinistral shear on the eastern margin of the rotating arc. The formation of the curvature seems not to have borne on the collision of the Izu-Ogasawara arc with Honshu, although the collision probably caused large-scale clockwise rotation of the Kanto Mountains in the east of the northward-convex structure.

1. Introduction

The southwest Japan arc has a zonal arrangement of geologic structures subparallel to its length, typically represented by the Median Tectonic Line (Fig. 1). The framework of this geologic feature has been built by longstanding accretion of oceanic materials to the edge of Eurasia due to plate subduction. The zonal arrangement runs roughly east-west, but it bends in a cusp form in central Honshu. Many geologists have tried to clarify the formation of this northward-convex structure (e.g., Matsuda, 1978; Amano, 1991; Niitsuma, 1999). The bending structure is generally attributed to the collision of the Izu-Ogasawara arc with central Honshu (Matsuda, 1978).

In the Tokai district of central Honshu, the zonal arrangement which is made of geologic belts, such as the Sanbagawa, Chichibu, and Shimanto, and boundary faults, such as the Median Tectonic Line, seems to curve from a latitudinal strike in the southwest to a longitudinal one in the northeast (Fig. 1). Previous paleomagnetic studies have dealt with the formation of the curvature and suggested that differential rotation of the Tokai and Hokuriku districts with respect to the central part of the southwest Japan arc (western Honshu including the San'in district) caused the curvature (Itoh, 1988; Itoh and Ito, 1989; Otofuji *et al.*, 1999). However, the timing of the differential rotation has not been determined precisely because of the scarcity of Middle Miocene or younger paleomagnetic data. Resolving this problem would be crucial to a better understanding of the tectonic evolution of central Honshu.

Well-dated Middle Miocene basalt dikes occur in the Shitara sedimentary basin located on the north of the curvilinear Median Tectonic Line in the Tokai district (Fig. 1). The basin is filled with thick Miocene strata named the Shitara Group (Kato, 1962), intruded by numerous north-south trending igneous dikes dated at about 15 Ma (Tsunakawa *et al.*, 1983). In this study, the remanence in these dikes was measured to investigate when the curvature formed. We show that the dikes record a northerly or southerly remanence direction, which indicates little or no rotation in the Shitara basin since 15 Ma. On the basis of our new results as well as previously reported data, we discuss the tectonic evolution of central Honshu from a paleomagnetic point of view.

The paleomagnetism of Miocene rocks in the Shitara basin has previously been studied (Tosha and Tsunakawa, 1981; Torii, 1983). Tosha and Tsunakawa (1981) reported site-mean directions from nine dikes that yielded a mean direction $D = 9.9^\circ$, $I = 72.5^\circ$, $\alpha_{95} = 13.3^\circ$. A steep inclination marked this direction and was attributed to a possible recording of a field transition or excursion. Torii (1983) collected samples from Lower Miocene sedimentary rocks and the overlying Middle Miocene volcanic rocks of the Shitara Group and unraveled a paleomagnetic rotation between them. In these studies, however, no description of

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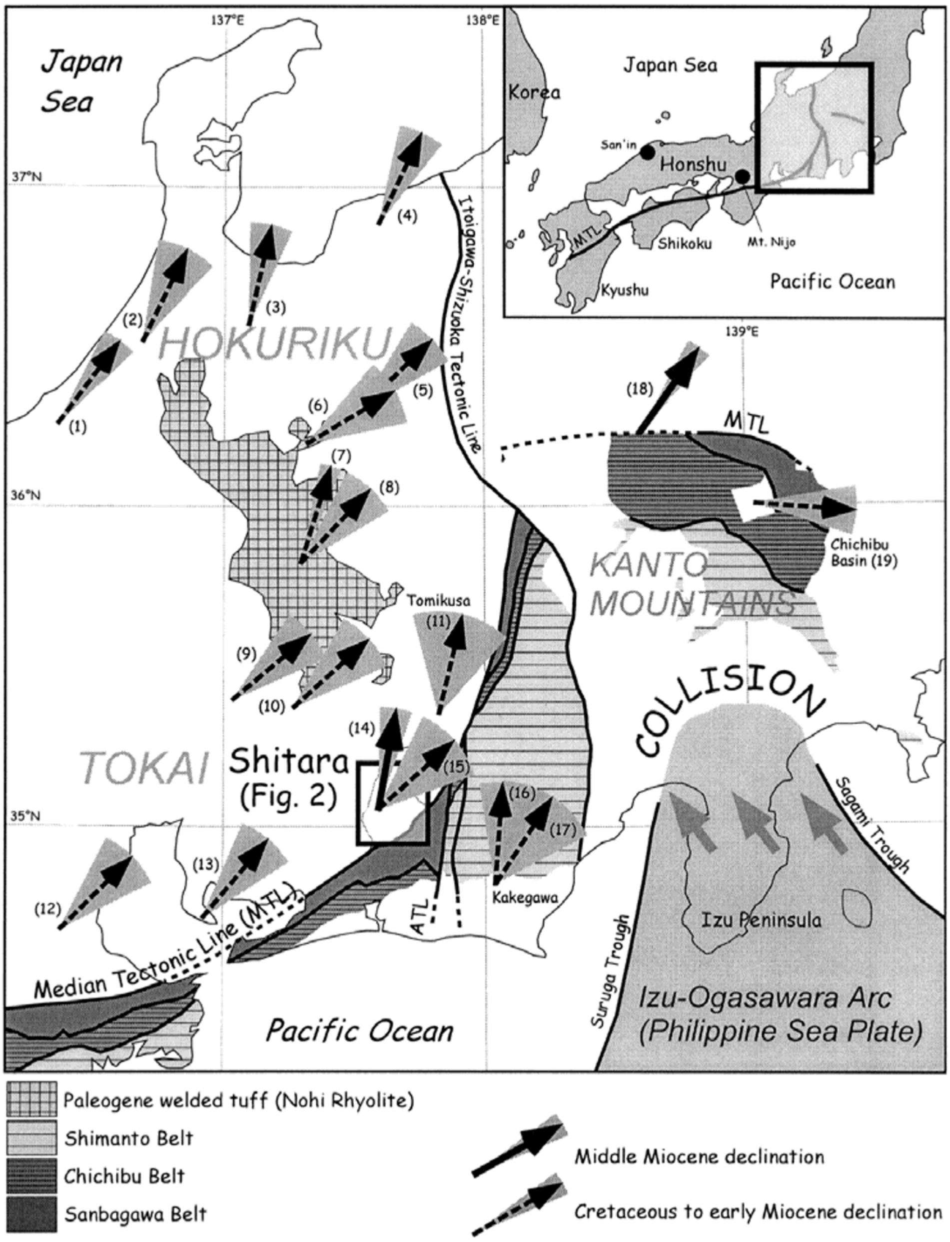

Fig. 1. Map of central Honshu showing the northward-convex form of zonal geologic structures. Also shown is location of the Shitara sedimentary basin. Paleomagnetic declinations are indicated by arrows along with the 95% confidence limits; all the paleomagnetic data shown here and their sources are summarized in the appendix (Table A1). ATL, Akaishi Tectonic Line.

tilt correction for the volcanic rocks is found, although various degrees of post-depositional tilting are actually seen in the field. For this reason the previously reported data from volcanic rocks of the Shitara Group were put aside in our tectonic consideration.

2. Materials and Methods

The Shitara Group is divided into the lower Hokusetsu and upper Nansetsu Subgroups (Fig. 2). The former consists mainly of Lower Miocene siliciclastic rocks, and the latter of various types of volcanic rocks of Middle Miocene age (Takada, 1988; Hoshi *et al.*, 2000). These rocks have been intruded by numerous north-south striking dikes, which comprise several swarms; two conspicuous examples are drawn in Fig. 2. The dikes consist mainly of basalt and andesite.

Our target is a north-south striking dike swarm in the northern part of the Shitara basin (Fig. 2). Two K-Ar dates, 14.9 ± 0.5 Ma and 16.5 ± 0.9 Ma, have been reported from dikes of this swarm (Tsunakawa *et al.*, 1983). Additionally, Uchiumi *et al.* (1990) reported a K-Ar date of 15.0 ± 0.7 Ma from a basalt flow considered to be the effusive facies of the dike swarm. Based on these dates, this dike swarm formed around 15 Ma. We collected samples along streams in approximately a 0.5 km^2 area (Fig. 3(a)). In this area, dikes consist of basalt with both aphyric and porphyritic textures and intrude gently (∼10° or less) tilted siliciclastic sediments of the Hokusetsu Subgroup. We found 26 dikes in to-

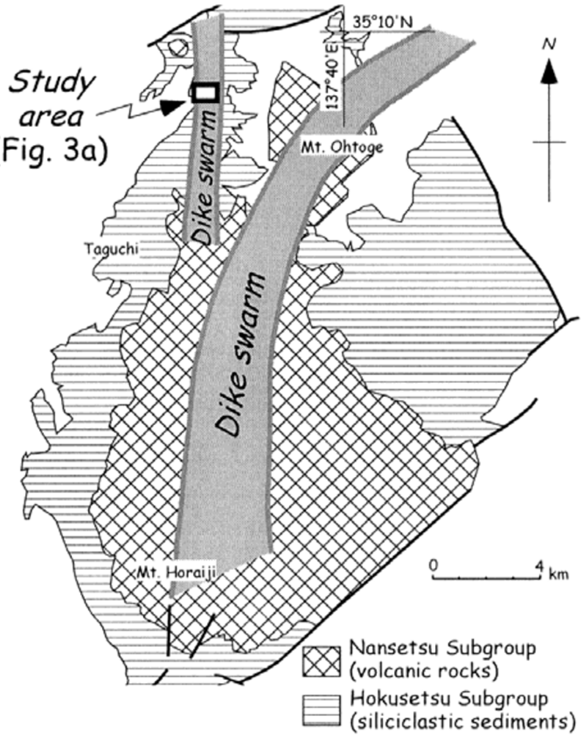

Fig. 2. Simplified geologic map of the Shitara basin showing location of the study area.

tal, and samples were collected from 25. Of these, about one third have a fresh aspect, being black or dark gray in color, and the rest show gray or white color due to alteration. The width of the dikes ranges from 0.3 to >30 m. The attitudes of intrusion surfaces are summarized in Fig. 3(b), in which it should be noted that most of the intrusion surfaces are vertical or steeply inclined. In Fig. 3(b), the solid circle shows the mean pole calculated from 25 poles to the intrusion surfaces. The mean pole is indistinguishable from the horizontal east-west axis at the 95% confidence level, demonstrating vertical occurrence. Along with the gentle dip of the country strata, this suggests little tilting of dikes after intrusion. Hence, tilt correction was not made for obtained remanence directions.

More than six core samples were taken by drilling each site and oriented with a magnetic compass. In the laboratory, one or two specimens of 22 mm long were cut from each core sample.

Measurement was made with a 2G cryogenic magnetometer in a field-free space at Kyoto University and a Schonstedt spinner magnetometer at Aichi University of Education. As a pilot study, two specimens per site were chosen for a detailed stepwise demagnetization experiment by conventional thermal and alternating-field techniques. Stepwise alternating-field demagnetization (AFD) was carried out in more than 10 steps up to 110 mT, and stepwise thermal demagnetization (ThD) was done in air in more than seven steps up to 610°C. Thermal alteration of magnetic minerals through heating was monitored by measuring magnetic susceptibility at each stage of the stepwise ThD.

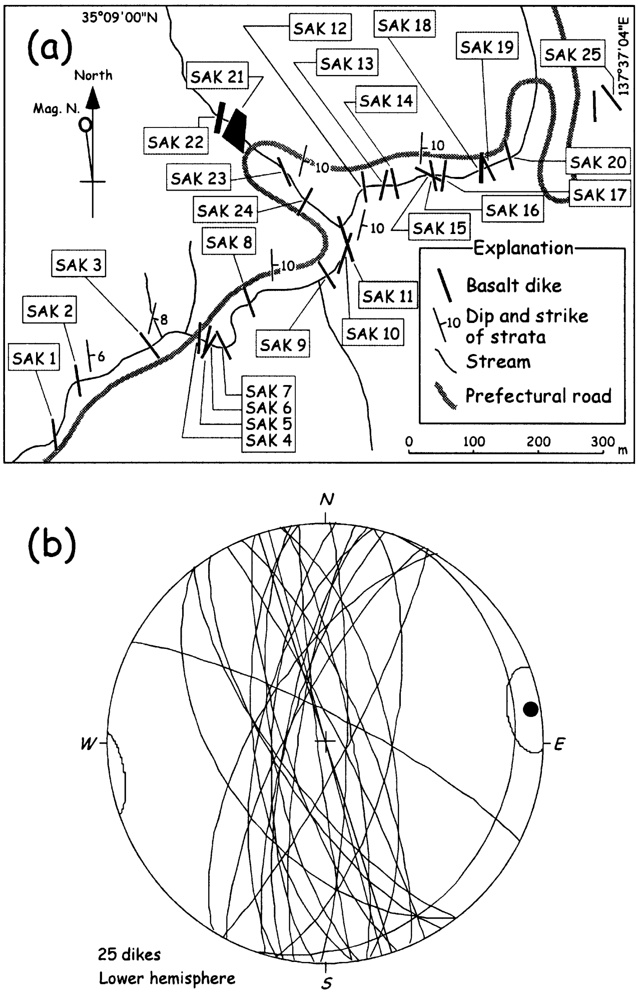

Fig. 3. (a) Geologic route map in the study area showing location of paleomagnetic sampling sites. (b) Lower-hemisphere equal-area projection of dike attitudes. The solid circle denotes the mean pole calculated from 25 poles to intrusion surfaces, and the oval about the mean pole indicates the 95% confidence region.

3. Results

3.1 Paleomagnetic direction

Examples of demagnetization results from the pilot specimens are shown in Fig. 4. Stable linear trajectories of magnetic vector endpoints were isolated from pilot specimens of 24 sites. Unstable magnetic components were successfully erased by 20 mT or 350°C. Many pilot specimens treated thermally showed a drastic increase in magnetic susceptibility at steps above 500°C. This was common to altered, gray- or white-colored rocks. In such specimens, somewhat anomalous directional behaviors were found above 500°C. For this reason the remaining specimens, except those of SAK6, were subjected to stepwise AFD, and the remaining specimens of SAK6 were treated by stepwise ThD, with the same demagnetization steps as the pilot study. The directions of stable linear trajectories were determined by fitting least-squares lines to the trajectories (Kirschvink, 1980).

SAK9 was the only site from which stable linear magnetic components were not obtained. It had the weakest NRM intensity of all the sites studied (Table 1). In addition, the AFD pilot specimen had a relatively hard viscous compo-

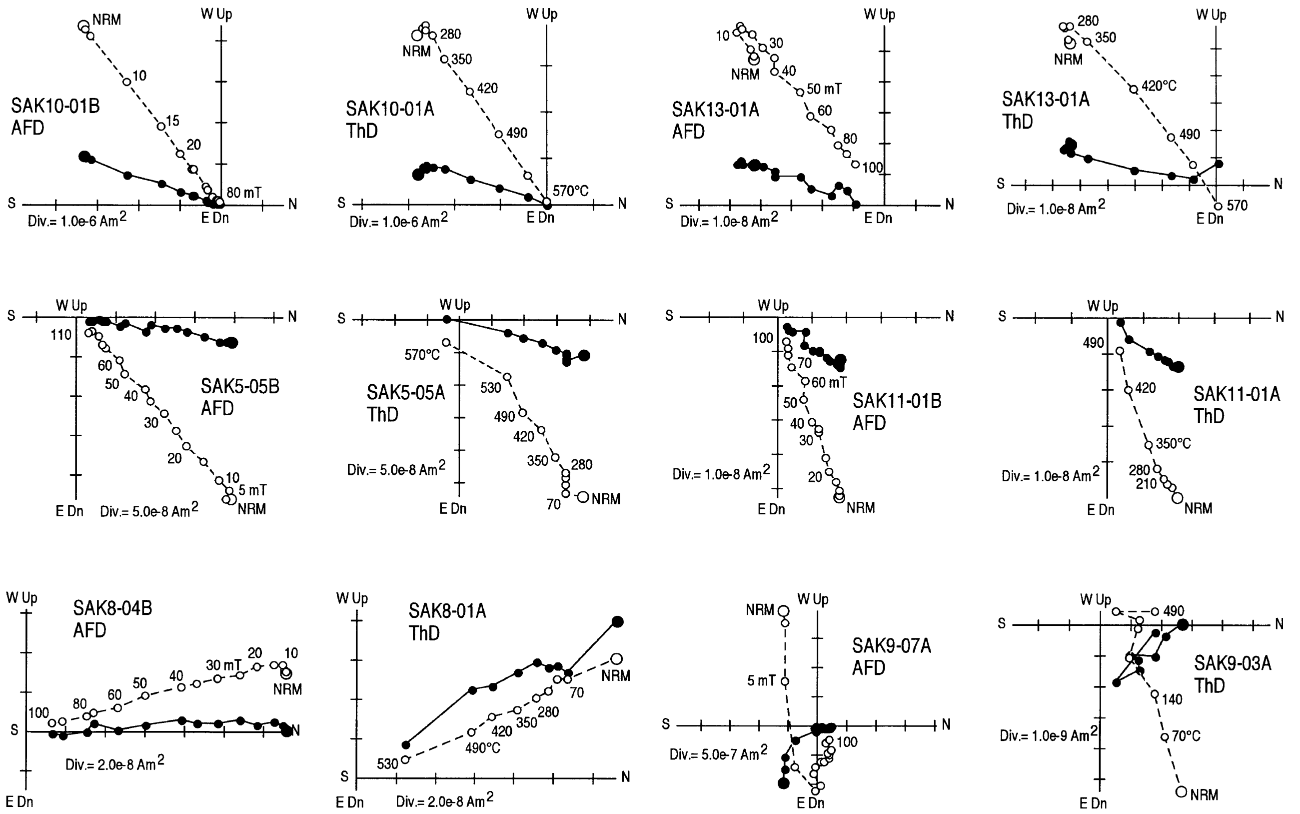

Fig. 4. Examples of stepwise demagnetization results from pilot specimens. Solid circles are vector endpoints projected onto the horizontal plane, and open circles indicate those onto the north-south vertical plane. AFD, alternating-field demagnetization; ThD, thermal demagnetization.

nent (Fig. 4). These observations are probably explained by the fact that the SAK9 samples consist of white-colored altered basalt. From the results of stepwise AFD, the primary magnetic polarity is inferred as normal.

Site-mean remanence data including statistic parameters (Fisher, 1953) are listed in Table 1 and plotted in Fig. 5. These are grouped into three based on their directions. Group A (number of sites, $N_A = 10$) is characterized by northerly declination and moderate inclination with normal polarity, and group B ($N_B = 11$) is characterized by southerly declination and moderate inclination with reversed polarity. Table 1 also summarizes group-mean remanence data. These two groups make a rough antipode and give a mean direction $D = 9.7°$, $I = 54.5°$, $\alpha_{95} = 5.2°$ ($N = 21$) after inverting the reversed-polarity site-means to the normal. Group C (3 sites) is anomalous, marked by northerly declination and shallow negative inclination.

3.2 Reversal test

To evaluate the anti-parallelism between groups A and B, we carried out the reversal test of McFadden and McElhinny (1990). Inverting one polarity group to another, we got an angle of 13.9° between the two mean directions. This value exceeded, at the 5% significance level, the critical angle (9.0°) determined by equation (15) of McFadden and McElhinny (1990), where the critical angle was calculated using quantities $N = 21$, R_A (length of vector sum for group A) $= 9.8018$, and R_B (that for group B) $= 10.8245$. This result indicates failure in the reversal test.

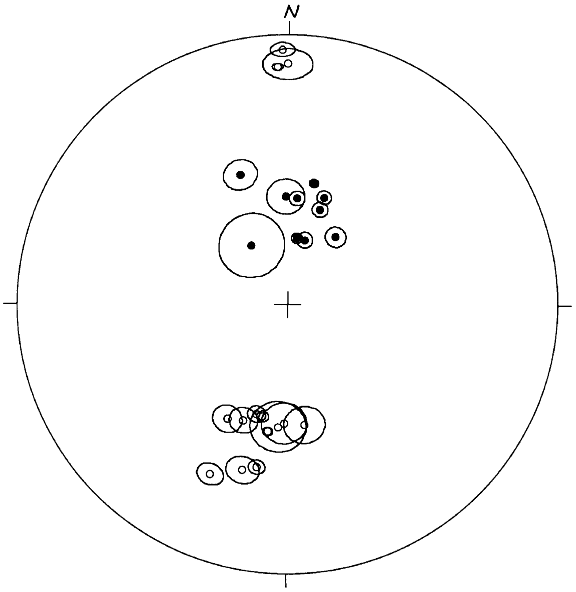

Fig. 5. Equal-area projection of site-mean remanence directions with 95% confidence ovals from 24 basalt dikes. Solid circles are directions on the lower hemisphere, and open circles are those on the upper hemisphere.

4. Discussion

4.1 Cause of the negative reversal test

The northerly declination of group A ($D \pm \Delta D = 5.6 \pm 15.2°$, where the 95% confidence limit $\Delta D = \arcsin(\sin\alpha_{95}/\cos I)$) is statistically said to be anti-parallel

Table 1. Remanence data from the Middle Miocene dikes, Shitara basin, central Honshu.

Site	(Lat. Long.)	S/D	N	J (mA/m)	D (°)	I (°)	α_{95} (°)	k	North VGP (°N)	North VGP (°E)	S_l (°)	S (°)	S_u (°)
Directional Group A													
SAK4	(35°08′42″N, 137°36′36″E)	183/70	7	18.6	14.6	69.9	2.4	657.1	68.7	161.8			
SAK5	(35°08′42″N, 137°36′37″E)	193/65	9	32.1	12.0	52.1	1.3	1537.9	79.8	237.9			
SAK6	(35°08′42″N, 137°36′37″E)	211/64	9	20.8	4.8	57.6	2.3	492.8	85.1	187.4			
SAK11	(35°08′46″N, 137°36′44″E)	162/90	5	4.2	35.2	65.0	3.1	626.5	61.2	192.4			
SAK14	(35°08′50″N, 137°36′48″E)	348/66	10	4.2	18.5	55.6	2.1	511.2	75.0	218.4			
SAK16	(35°08′51″N, 137°36′50″E)	349/80	8	1.6	7.7	69.8	1.6	1255.0	70.7	151.5			
SAK17	(35°08′51″N, 137°36′51″E)	188/80	8	814.7	18.6	59.6	2.3	560.2	74.4	202.2			
SAK18	(35°08′51″N, 137°36′53″E)	001/82	5	5.8	339.6	47.6	4.8	253.5	71.6	32.9			
SAK22	(35°08′54″N, 137°36′37″E)	191/75	6	46.0	358.7	57.1	5.5	152.1	87.2	115.8			
SAK25	(35°08′55″N, 137°37′01″E)	143/72	5	1.2	328.3	69.1	9.8	61.4	61.6	95.5			
Mean direction (10 site-means)					5.6	61.5	7.2	45.4					
Mean pole (10 VGPs)							($A_{95} = 10.1°$)		80.4	164.3	12.9	16.7	23.6
Directional Group B													
SAK1	(35°08′37″N, 137°36′27″E)	173/87	14	15.4	190.4	−38.2	2.3	303.1	73.6	281.2			
SAK2	(35°08′40″N, 137°36′27″E)	171/70	6	28.4	194.8	−36.2	4.5	219.2	70.1	272.8			
SAK3	(35°08′42″N, 137°36′32″E)	143/50	11	188.0	192.1	−54.6	1.7	724.7	80.1	224.2			
SAK7	(35°08′42″N, 137°36′38″E)	153/76	7	100.9	188.5	−50.2	1.4	1905.7	81.7	255.6			
SAK10	(35°08′46″N, 137°36′44″E)	018/15	7	537.8	195.3	−54.9	2.6	538.5	77.5	221.9			
SAK12	(35°08′50″N, 137°36′46″E)	173/63	5	36.5	171.8	−52.4	5.9	171.8	82.9	32.4			
SAK13	(35°08′50″N, 137°36′47″E)	013/65	6	6.8	200.4	−51.7	4.1	263.3	72.8	231.2			
SAK15	(35°08′51″N, 137°36′50″E)	297/80	4	2.1	184.1	−52.0	8.0	493.1	85.8	263.0			
SAK19	(35°08′51″N, 137°36′53″E)	333/85	5	47.8	204.1	−31.2	3.6	442.2	61.8	261.8			
SAK20	(35°08′52″N, 137°36′54″E)	165/90	3	16.6	207.2	−50.1	4.3	815.9	66.9	230.5			
SAK21	(35°08′53″N, 137°36′38″E)	208/76	8	21.8	181.4	−53.2	6.5	74.0	88.2	277.4			
Mean direction (11 site-means)					192.4	−48.1	6.1	57.0					
Mean pole (11 VGPs)							($A_{95} = 6.3°$)		78.5	252.5	8.7	11.1	15.4
A + B mean direction (21 site-means)					9.7	54.5	5.2	38.0					
A + B mean pole (21 VGPs)							($A_{95} = 6.2°$)		82.3	216.6	12.8	15.6	20.0
Directional Group C													
SAK8	(35°08′44″N, 137°36′39″E)	161/75	8	10.5	357.2	−13.0	1.3	1700.1	48.2	321.8			
SAK23	(35°08′51″N, 137°36′41″E)	337/75	5	1.0	359.7	−11.9	5.9	171.7	48.8	318.1			
SAK24	(35°08′49″N, 137°36′39″E)	028/82	6	1.3	358.5	−6.3	2.8	576.2	51.7	320.0			
Mean direction (3 site-means)					358.5	−10.4	5.8	455.7					
Mean pole (3 VGPs)							($A_{95} = 3.4°$)		49.6	320.0			
Other													
SAK9	(35°08′45″N, 137°36′43″E)	148/70	2	0.4									

S/D, strike/dip of intrusion; N, number of specimens used for site-mean calculation; J, intensity of natural remanence; D, declination; I, inclination; α_{95}, radius of 95% confidence region of site mean direction; k, precision parameter; VGP, virtual geomagnetic pole; S, angular standard deviation (ASD) of VGPs; S_l and S_u, lower and upper 95% confidence limits for ASD; A_{95}; radius of 95% confidence region of paleomagnetic pole.

to the southerly one of group B ($D \pm \Delta D = 192.4 \pm 9.2°$). In contrast, the inclination of group A ($I \pm \Delta I = 61.5 \pm 7.2°$, where the 95% confidence limit $\Delta I = \alpha_{95}$) is not anti-parallel to that of group B ($I \pm \Delta I = -48.1 \pm 6.1°$), probably leading to the failure in the reversal test. Two possibilities might exist to explain the negative result, as discussed below.

As widely known, a negative reversal test may be achieved if a remanence includes a secondary component in spite of demagnetization (Cox and Doell, 1960; McElhinny, 1973). If there remains a stable secondary component, it would bias both groups of polarity to the same direction. Assuming that both A and B groups have an inerasable component parallel or subparallel to the present geomagnetic field, it would be possible to explain the fact that the inclination does not show an anti-parallelism. In such a particular case, when one of the groups is converted to another polarity and their mean direction is then calculated, the vector sum tends to cancel out the secondary component (McElhinny, 1973). Calculating the mean of the mean directions of groups A

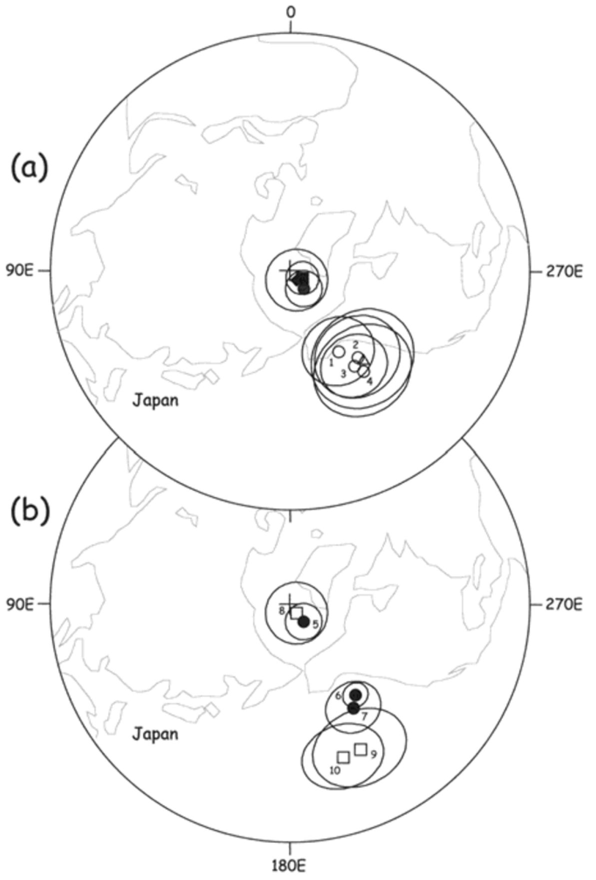

Fig. 6. Polar equal-area projections showing comparison of the paleomagnetic pole from the ∼15 Ma Shitara dikes with those from other areas. Data sources are summarized in Table 2. In (a), the solid circle is the ∼15 Ma Shitara pole; the solid square is the Early to Middle Miocene pole from the North China Block; the solid diamond is the ∼15 Ma pole from the Omori Formation in San'in; the open triangle is the Early Miocene pole from the Hokusetsu Subgroup in the Shitara basin; and open circles are poles from the Lower Miocene series in Tokai (1, Morozaki Group; 2, Ichishi Group; 3, Kani Group; 4, Mizunami Group). In (b), solid circles are poles from Tokai (5, ∼15 Ma Shitara dikes; 6, Early Miocene mean calculated from data from the Hokusetsu, Morozaki, Ichishi, Kani, and Mizunami Groups; 7, Paleogene Nohi Rhyolite); and open squares are poles from San'in (8, ∼15 Ma Omori Formation; 9, Early Miocene Hata Formation; 10, Paleogene Sakurae Group). 95% confidence limits with radius A_{95} are shown surrounding each mean pole.

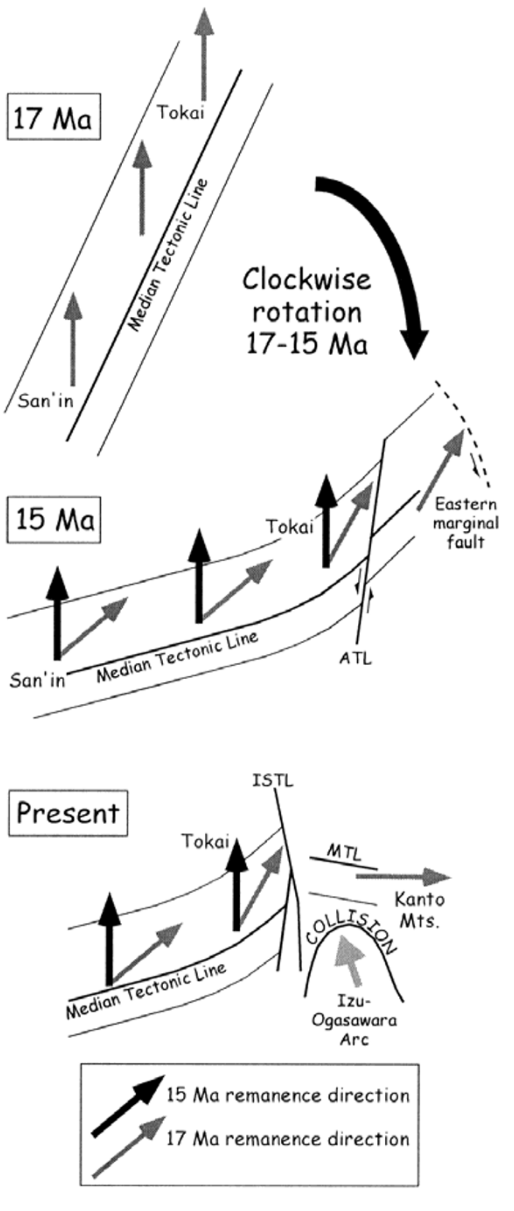

Fig. 7. Model for the clockwise rotation of the southwest Japan arc and the formation of curvature of the zonal geologic arrangement at the eastern part of the arc.

and B, we get a direction of $D = 9.6^\circ$ and $I = 54.8^\circ$, which is almost identical with the mean direction from 21 site-mean directions of groups A and B (Table 1). We believe secondary components have been erased effectively by thorough stepwise demagnetization (Fig. 4), but, even if an inerasable secondary component still exists, the mean direction determined from the 21 site-means probably represents a paleomagnetic direction in the study area at about 15 Ma.

A negative reversal test can also be produced if a mean direction does not average out the secular variation thoroughly. Our result includes both normal and reversed polarities and hence samples at least a time span of one polarity-reversal; nevertheless, this possibility should be examined carefully. We thus tested this by studying the angular standard deviation (ASD) of virtual geomagnetic poles (VGPs). Following Cox (1969), the 21 VGPs of groups A and B gave an ASD of 15.6° with lower and upper 95% confidence limits (S_l and S_u) of 12.8° and 20.0°, respectively. This ASD value is quite similar to the 0–5 Ma global trend (15.74°, $S_l = 15.08^\circ$, $S_u = 16.46^\circ$) obtained for the latitude range 35.0–39.9°N from a worldwide database (McElhinny and McFadden, 1997). Therefore, we consider the mean direction determined from the 21 site-means is a paleomagnetic direction in which the secular variation is adequately averaged out, so this possibility can be discarded. In this connection, the group C remanence is probably an instantaneous recording of the past field because of its very small dispersion (Table 1). Remanence acquisition during a field transition or excursion could have resulted in its anomalous direction.

4.2 Tectonic implications

A northerly declination and an inclination similar to that expected in the geocentric axial dipole field (54.6°) mark

Table 2. Summary of the paleomagnetic poles shown in Fig. 6.

					North paleomag. pole			
Area	Geologic unit	(N. lat., E. long.)	Age	N	(°N)	(°E)	A_{95} (°)	Ref.
Tokai (SW Japan)	Shitara dikes	(35.1°, 137.6°)	∼15 Ma	21	82.3	216.6	6.2	This study
	Hokusetsu Subgroup	(35.1°, 137.6°)	Early Miocene	4	50.0	219.2	17.2	Torii (1983)
	Ichishi Group	(34.7°, 136.4°)	Early Miocene	11	51.9	217.7	14.3	Hayashida and Ito (1984)
	Morozaki Group	(34.7°, 136.9°)	Early Miocene	12	57.4	210.6	12.0	Hayashida (1986)
	Mizunami Group	(35.4°, 137.2°)	Early Miocene	7	46.6	215.8	16.1	Hayashida (1986)
	Kani Group	(35.4°, 137.1°)	Early Miocene	6	50.0	213.6	11.0	Hayashida *et al.* (1991)
	Early Miocene mean (5 units)				51.2	215.5	4.2	
	Nohi Rhyolite	(36°, 137°)	Paleogene	14	47.8	211.3	9.0	Otofuji *et al.* (1999)
San'in (SW Japan)	Omori Formation	(35°, 133°)	∼15 Ma	18	86.1	214.0	10.5	Otofuji *et al.* (1991)
	Hata Formation	(35°, 133°)	Early Miocene	6	32.9	205.7	14.5	Otofuji and Matsuda (1984)
	Sakurae Group	(35°, 132°)	Paleogene	14	32.4	199.0	12.4	Otofuji and Matsuda (1987)
North China Block		(36°, 119°)	Early to Middle Mio.	12	85.2	238.4	5.6	Zhao *et al.* (1994)

N, number of virtual geomagnetic poles used to calculate paleomagnetic pole; A_{95}, radius of 95% confidence region of paleomagnetic pole.

the mean direction of groups A and B (Table 1), suggesting little or no tectonic motion in the study area. To examine this quantitatively, we compared the paleomagnetic pole from the dikes studied with those from the other areas (Table 2 and Fig. 6). The north paleomagnetic pole from the Shitara dikes (82.3°N, 216.6°E, and $A_{95} = 6.2°$) is plotted in Fig. 6(a) by the solid circle; also plotted are the Early to Middle Miocene paleomagnetic pole from the North China Block (NCB) in the Asian continent (Zhao *et al.*, 1994) (solid square) and the ∼15 Ma pole from the Omori Formation of the San'in district in the central part of the southwest Japan arc (Otofuji *et al.*, 1991) (solid diamond). These pole positions are indistinguishable from each other, which indicates no paleomagnetically detectable rotation and poleward movement in the southwest Japan arc since about 15 Ma.

On the other hand, Early to Middle Miocene clockwise rotation is inferred in the Tokai district. The paleomagnetic pole from the Lower Miocene Hokusetsu Subgroup in the Shitara basin (Torii, 1983) is plotted in Fig. 6(a) by the open triangle. Despite a relatively large 95% confidence limit, it differs significantly from those from both the Shitara dikes and the NCB. However, it is in turn indistinguishable from Early Miocene poles from Tokai (shown by open circles in Fig. 6(a)). No significant difference is found among the Early Miocene poles, giving a grand-mean pole at 51.2°N, 215.5°E, $A_{95} = 4.2°$. Recent biostratigraphic studies (Ito *et al.*, 1999; Hoshi *et al.*, 2000) showed that the Lower Miocene groups in Tokai are correlated to the diatom *Crucidenticula sawamurae* Zone that spans between nearly the base of chron C5D (∼18 Ma) and the middle of chron C5C (∼17 Ma) on the geomagnetic polarity time scale (Yanagisawa and Akiba, 1998). Following Demarest (1983), we get a clockwise rotation $R \pm \Delta R = 38 \pm 7°$ to account for the difference between the position of the Shitara dikes pole and that of the Early Miocene grand-mean pole. Thus, ∼40° clockwise rotation occurred in Tokai between the deposition of the Lower Miocene groups (18–17 Ma) and about 15 Ma.

In the southwest Japan arc, differential rotation of its eastern part including the Tokai and Hokuriku districts with respect to its central part including the San'in district has been documented (Itoh, 1988; Itoh and Ito, 1989; Otofuji *et al.*, 1999). Paleomagnetic poles from Tokai and San'in are summarized in Table 2 and shown in Fig. 6(b). In Fig. 6(b), poles from Tokai are shown by solid circles (5 = ∼15 Ma pole from the Shitara dikes, 6 = Early Miocene grand-mean pole describe above, 7 = Paleogene pole from the Nohi Rhyolite reported by Otofuji *et al.* (1999)), and those from San'in are shown by open squares (8 = ∼15 Ma pole from the Omori Formation, 9 = Early Miocene pole from the Hata Formation (Otofuji and Matsuda, 1984), 10 = Paleogene pole from the Sakurae Group (Otofuji and Matsuda, 1987)). In each district, no significant difference is found between the Early Miocene pole and the Paleogene one. However, there is a difference between the Early Miocene and Paleogene poles of Tokai (6 and 7 in Fig. 6(b)) and those of San'in (9 and 10), in spite of the almost identical position at about 15 Ma (5 and 8). Comparison of poles shows a clockwise rotation $R \pm \Delta R = 65 \pm 17°$ in San'in between ∼20 Ma (age of the Hata Formation: Otofuji and Matsuda, 1984) and ∼15 Ma (Omori Formation). This amount of rotation is 27° larger than in Tokai. Thus, as Itoh (1988), Itoh and Ito (1989), and Otofuji *et al.* (1999) pointed out, the eastern part of the southwest Japan arc rotated counterclockwise with respect to the central part. Our results from the Shitara dikes constrain the timing of this differential rotation; the rotation had ceased by about 15 Ma.

The Early to Middle Miocene clockwise rotation in Tokai and San'in is attributed to the clockwise rotation of the southwest Japan arc associated with the opening of the Japan Sea (Torii, 1983; Otofuji *et al.*, 1991; Hayashida *et al.*, 1991). The precise timing of the clockwise rotation has been at issue, but our data suggest that the rotation had ceased by about 15 Ma. We feel that more data are needed to enhance

Table A1. Summary of the paleomagnetic directional data shown in Fig. 1. Numbers (No.) correspond to those in Fig. 1.

No.	Area	(N. lat., E. long.)	Age	D (°)	dD (°)	I (°)	α_{95} (°)	Ref.
1	Daishoji	(36.3°, 136.3°)	Early Mio.	36.5	10.2	53.9	6.0	Itoh and Ito (1989)
2	Kanazawa	(36.5°, 136.7°)	Early Mio.	25.6	17.0	49.3	11.0	Itoh and Ito (1989)
3	Yatsuo	(36.6°, 137.1°)	Early Mio.	13.0	11.9	52.7	7.2	Itoh (1988)
4	Uozu	(36.8°, 137.5°)	Paleogene	25.2	13.4	55.6	7.5	Itoh and Ito (1988)
5	Kasagatake	(36°, 137°)	Paleogene	45.8	14.6	40.1	11.1	Otofuji *et al.* (1999)
6	Oamamiyama	(36°, 137°)	Late Cret.	58.9	18.8	61.7	8.8	Otofuji *et al.* (1999)
7	Nohi	(36°, 137°)	Late Cret.	17.0	9.5	49.8	6.1	Itoh (1988)
8	Nohi	(36°, 137°)	Late Cret.	43.0	16.4	51.5	10.1	Otofuji *et al.* (1999)
9	Kani	(35.4°, 137.1°)	Early Mio.	49.9	16.3	53.2	9.7	Hayashida *et al.* (1991)
10	Mizunami	(35.4°, 137.2°)	Early Mio.	48.4	17.9	48.3	11.8	Hayashida (1986)
11	Tomikusa	(35.3°, 137.8°)	Early Mio.	13.4	27.9	55.4	15.4	Hayashida (1992)
12	Ichishi	(34.7°, 136.4°)	Early Mio.	45.1	18.2	48.8	11.9	Hayashida and Ito (1984)
13	Morozaki	(34.7°, 136.9°)	Early Mio.	40.3	17.3	55.5	9.7	Hayashida (1986)
14	Shitara	(35.1°, 137.6°)	Middle Mio.	9.7	9.0	54.5	5.2	This study
15	Shitara	(35.1°, 137.6°)	Early Mio.	48.0	22.1	50.0	14.0	Torii (1983)
16	Kakegawa	(34.8°, 138.0°)	Early Mio.	4.4	12.5	59.6	6.3	Hayashida (1994)
17	Kakegawa	(34.8°, 138.0°)	Early Mio.	32.7	29.3	58.3	14.9	Hiroki and Matsumoto (1999)
18	Uchiyama	(36.3°, 138.6°)	Middle Mio.	34.7	7.0	51.2	4.4	Takahashi and Watanabe (1993)
19	Chichibu	(36.0°, 139.0°)	Early Mio.	93.7	13.8	52.7	8.3	Hyodo and Niitsuma (1986)

D, declination; dD, 95% confidence limit for declination; I, inclination; α_{95}, radius of 95% confidence region of mean direction.

the reliability of age of the Shitara dikes, but the age of 15 Ma as the upper limit is strengthened by a recent result by Hoshi *et al.* (2000). They dated a northerly remanence in volcanic rocks of the Mt. Nijo area at 14.6 Ma or older by magnetostratigraphic dating. Most of the clockwise rotation of the southwest Japan arc probably occurred between 17 and 15 Ma.

Figure 7 illustrates a model for the clockwise rotation of the southwest Japan arc and intra-arc differential rotation. The clockwise rotation and differential rotation took place simultaneously between 17 and 15 Ma. The differential rotation resulted in the formation of curvature of the zonal geologic arrangement. Macroscopically, the deformation in the eastern part of the southwest Japan arc was probably in a ductile manner (Itoh and Ito, 1989). Otofuji *et al.* (1999) pointed out that the Akaishi Tectonic Line (ATL) acted as a major boundary fault, with which we fundamentally agree. Left-lateral movement along the ATL at about 15 Ma probably caused local rotation that affected an initially northeasterly Early Miocene remanence in Tomikusa to become a less deflected one (Hayashida, 1992) (Fig. 1). Conflicting results have been reported from Lower Miocene sediments of Kakegawa (Hayashida, 1994; Hiroki and Matsumoto, 1999); a northerly remanence was reported by Hayashida (1994), while we can get a northeasterly mean direction by adopting only the reversed-polarity site-means determined by Hiroki and Matsumoto (1999). Most of the site-means of normal polarity measured by Hiroki and Matsumoto (1999) have a direction close to the geocentric axial dipole field direction in situ, so they would be affected by a viscous component. We feel further paleomagnetic studies are needed for Kakegawa, and in the model we leave the Kakegawa data out of consideration.

Two different possibilities for the cause of the differential rotation have been illustrated (Itoh, 1988). One is that left-lateral shear produced on the eastern margin of the rotating southwest Japan arc resulted in a counterclockwise rotation of the eastern part of the southwest Japan arc relative to the central part. Another interpretation is that the Izu-Ogasawara arc collided with central Honshu, causing counterclockwise rotation of the region west of the ISTL and clockwise rotation of the Kanto Mountains. In the Kanto Mountains, a more than 90° clockwise rotation is inferred to have occurred since the Early Miocene (Hyodo and Niitsuma, 1986). Half of this rotation could have resulted from the clockwise rotation of the southwest Japan arc and the rest occurred after 12 Ma, probably related to the collision of the Izu-Ogasawara arc (Takahashi and Watanabe, 1993). Geologic observations suggest multiple collision events of buoyant crustal masses of the Izu-Ogasawara arc since at least Middle Miocene time (Amano, 1991). However, our model indicates that the formation of curvature of the zonal geologic arrangement west of the ISTL was not related to the Middle Miocene or later collision of the Izu-Ogasawara arc. The simultaneity of the differential rotation with the clockwise rotation of the southwest Japan arc strongly suggests the formation of the curvature associated with the sinistral shear produced on the eastern margin of the rotating arc. Intra-arc differential rotation also occurred in the western part of the southwest Japan arc during the opening of the Japan Sea (Ishikawa, 1997); about 30° counterclockwise rotation of northern Kyushu relative to the central part of the arc is suggested from paleomagnetic data.

5. Conclusions

The paleomagnetism of Middle Miocene dikes in the Shitara basin leads us to conclude that the curvature of the zonal geologic arrangement in the west of the cusp structure in central Honshu formed when the southwest Japan arc rotated clockwise between 17 and 15 Ma. This deformation was associated with differential rotation of the eastern part of the southwest Japan arc with respect to the central part that probably resulted from the sinistral shear on the eastern margin of the rotating arc. The Middle Miocene or later collision of the Izu-Ogasawara arc with Honshu seems not to have caused the curvature in the west of the cusp structure, although it caused the Kanto Mountains in the east to rotate clockwise.

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Appendix

The data shown in Fig. 1 are listed in Table A1.

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