Evolutionary Models of Convergent Margins : Origin of Their Diversity

Chapter 8

Paleomagnetic Studies on Miocene Sequences of Hokutan and Tottori Groups in Southwest Japan: Implications for Middle Miocene Rotational Movement of Southwest Japan Block Associated with the Japan Sea Opening

Naoto Ishikawa, Takashi Suzuki and Shiro Ishida

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Abstract

Miocene sequences composed of volcanic rocks and overlying marine sediments distributing at the Japan Sea side of Southwest Japan have been considered to form related to the rifting and subsequent spreading of the Japan Sea back-arc basin in Miocene time. We performed paleomagnetic investigations on the sequences in the eastern San'in district, the Hokutan and Tottori Groups. Paleomagnetic analyses on samples from 33 sites indicated that characteristic magnetic components from five sites of volcanic rocks in the Hokutan Group and from four sites of marine sediments in the Tottori Group were regarded as primary components. An obtained paleomagnetic direction of the volcanic rocks has an easterly deflected declination (D = 23.9° ± 20.2°), while that of the marine sediments shows no significant deflection in declination (D = 17.8° ± 19.1°). Through the comparison with paleomagnetic data from the Miocene sequences in Southwest Japan, it is suggested that magnetic polarities of the volcanic and sedimentary sequences are assigned to C5Cn and C5Br-C5Bn, respectively, and that the eastern San'in district suffered a clockwise rotation of 24° at around 16 Ma after the early Miocene volcanic activity and before the middle Miocene marine transgression in the whole clockwise rotation process of Southwest Japan related to the Japan Sea opening.

Keywords: Southwest Japan, Japan Sea, paleomagnetism, clockwise rotation, Miocene, marine transgression

1. Introduction

In the San'in and Hokuriki districts on the Japan Sea side of Southwest (SW) Japan, Miocene sequences characterized by the lower volcanic units and the upper marine sedimentary ones are distributed mainly at three areas (**Figure 1**): the Hokuriku Group in the Hokuriku district, and the Hokutan/Tottori Groups, and the Iwami Group in the eastern and central parts of the San'in district, respectively. The lower volcanic units are composed of subaerial volcanic and pyroclastic rocks formed by intensive volcanic activities in early Miocene time, and the upper marine sedimentary sequences are characterized by an upward change in lithofacies from conglomerate and sandstone under shallow marine environment at its basal part to well-stratified mudstone under deep marine environment, indicating a marine transgression and subsequent rapid subsidence of sedimentary basins in middle Miocene time [1–6]. The Miocene sequences have been considered to form related to the rifting and subsequent spreading of the Japan Sea back-arc basin in Miocene time [3].

Paleomagnetic investigations in SW Japan, including researches on the Miocene sequences, have revealed a clockwise (CW) rotation of SW Japan in middle Miocene time associated with the formation of the Japan Sea [7–14]. Numerical analyses on compiled paleomagnetic

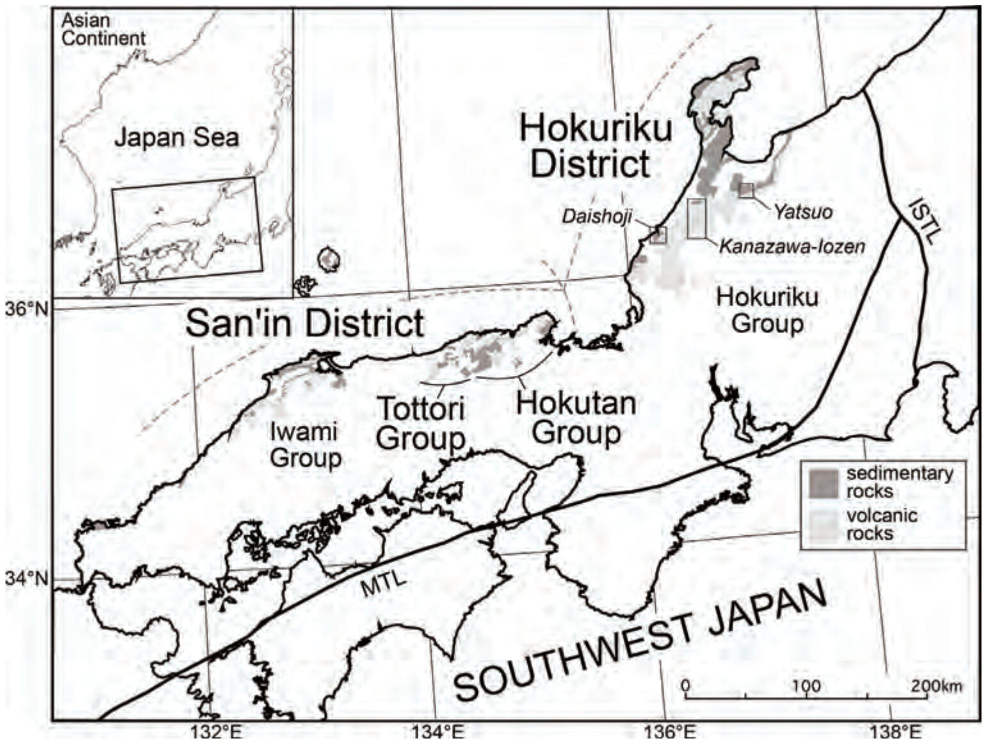

Figure 1. Map showing the distribution of Miocene volcanic and sedimentary sequences at the Japan Sea side in Southwest Japan modified from Ref. [21]. MTL: Median Tectonic Line. ISTL: Itoigawa-Shizuoka Tectonic Line.

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data with geochronological age controls [7] indicated that SW Japan was rotated clockwise through about 47° at about 15 Ma for the duration as short as less than 1 m.y. A pivot of the rotation for SW Japan as a coherent block has been estimated between the Korean Peninsula and the western toe of the SW Japan block, and a rapid fan-shape opening of the Japan Sea has been proposed as an opening mode at the climax stage in the formation process of the Japan Sea [7, 15]. Shallow marine deposits at the basal part of the upper marine sedimentary units of the Miocene sequences provide molluscan fossils referred to the Kadonosawa Fauna [16] indicating subtropical to tropical environment [17]. Chinzei et al. [18, 19] suggested that the Kadonosawa Fauna are found in the strata assigned to the N8 and the lower N9 zones of planktonic foraminiferal biostratigraphy of Blow [20], and that the occurrence of the Kadonosawa Fauna in 16.5–15 Ma is attributed to a regional change in paleogeography around the Japan Sea related to the rapid CW rotation of SW Japan.

In order to clarify the temporal and regional relationship between the CW rotation of SW Japan and tectonic events related to the Japan Sea formation recorded in on-land geology in more detail, paleomagnetic and magnetostratigraphic investigations are still indispensable. We applied the investigations to the Miocene sequences of the Hokutan and Tottori Groups in the eastern San'in district (**Figure 1**). Paleomagnetic data from the two groups are rare, although strenuous paleomagnetic studies have been carried out for the Miocene sequences of the Hokuriku Group in the Hokuriku district mainly with magnetobiostratigraphic analyses and the Iwami Group in the central San'in district with radiometric age dating [8, 11, 13, 14] as mentioned later. We regarded the strata including the Kadonosawa Fauna as key beds, which are considered to represent the initiation of the marine transgression in middle Miocene time, and sampled volcanic and pyroclastic rocks, and sedimentary ones below and above the key bed along several sampling routes.

2. Geological setting and sampling

Paleomagnetic samplings were performed on the Hokutan Group distributed in Yakuno-Wadayama area around Mt. Kanatoko at the northern area of Kyoto and Hyogo Prefectures and the Tottori Group at the eastern part of Tottori Prefecture (**Figure 2**).

The Hokutan Group is divided into five formations, namely the Takayanagi, Yoka, Toyooka, Amino, and Tango Formations in ascending order [2, 22]. In the Yakuno-Wadayama area, the Yoka and Toyooka Formations are distributed, overlying the Takayanagi Formation of a basal conglomerate for the Hokutan Group [23, 24]. The Yoka Formation consists mainly of basaltic to andesitic lavas and pyroclastics. K-Ar ages of 19–20 Ma were reported from the Yoka Formation [25]. The Toyooka Formation is composed mainly of conglomerate and sandstone intercalating acidic to intermediate volcanics and is considered to have formed in sedimentary environment of lacustrine in lower and middle part and of shallow marine in the upper part [1]. Molluscan fossils of the Kadonosawa Fauna were found in the Toyooka Formation [24, 26]. The Amino Formation is composed mainly of alternations of sandstone and mudstone deposited in marine environment, which is accompanied with acidic to intermediate volcanics [1, 2, 22]. Planktonic foraminiferal fossils assigned to the lower part of Zone N9 of Blow [20] were found from mudstone layers in the lower part of the Amino

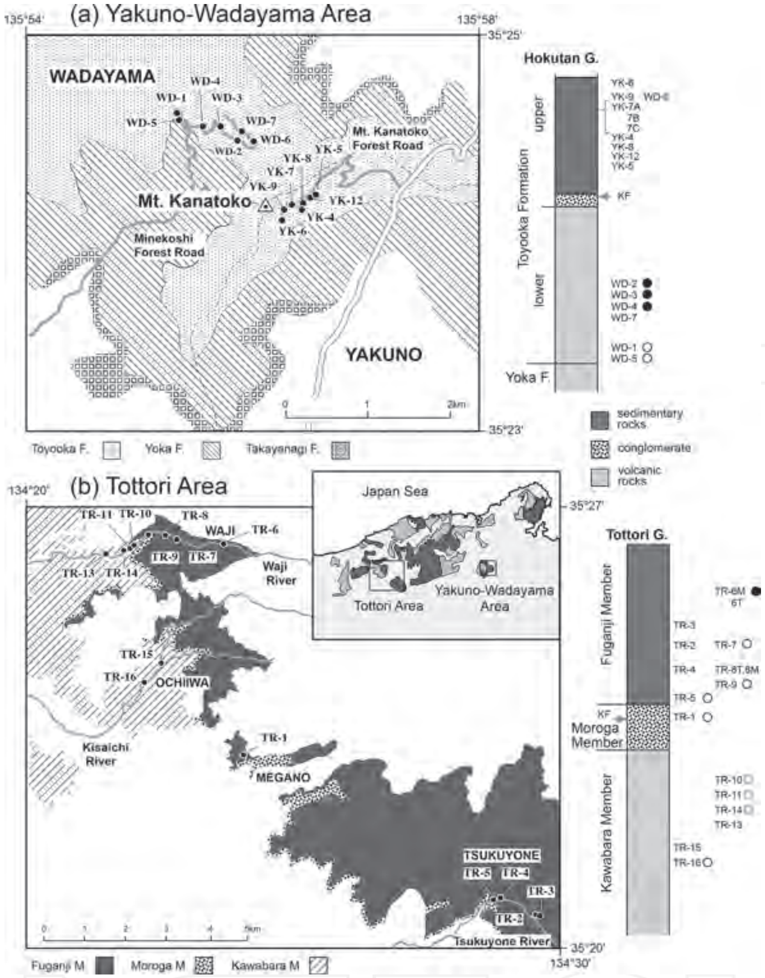

Figure 2. Simplified geological maps of (a) the Yakuno-Wadayama area around Mt. Kanatoko after [23] and (b) the Tottori area after [29]. Solid circles on the maps indicate locations of paleomagnetic sampling sites. Generalized columnar sections of (a) the Hokutan Group in the Yakuno-Wadayama area after [2] and (b) the Tottori Group after Ref. [29]. Relative stratigraphic positions for horizons of paleomagnetic sites and detected magnetic polarities are shown beside the columnar sections. Solid (open) circle denotes normal (reverse) polarity, and open squares denote transitional polarities (see in the text). KF: horizons providing molluscan fossils referred to the Kadonosawa Fauna.

Formation [27]. K-Ar ages of 13.5–14.9 Ma were reported for rhyolite samples from the middle part of the Amino Formation [22]. The Tango Formation consists mainly of andesitic to dacitic pyroclastics, lavas, and intrusive rocks [2, 22], and K-Ar ages of 13.9 and 14.6 Ma were reported from intrusive rocks of the formation [22].

In the Yakuno-Wadayama area, volcanic sequences consisting of andesite lavas and dacitic pyroclastic rocks in the lower part of the Toyooka Formation and sedimentary ones consisting of conglomerate, sandstone, and alternation of sandstone and mudstone intercalating tuffs and andesite lavas in the upper part of the formation were exposed along two forest roads (**Figure 2**). From sandstone layers above a conglomerate bed overlying pyroclastic rocks at the boundary between the volcanic and sedimentary sequences, molluscan fossils referred to the Kadonosawa Fauna were found [24].

The Tottori Group in our sampling area is divided into two formations: the Yazu and Iwami Formations in ascending order [4, 5, 28]. The Yazu Formation consists mainly of thick piles of volcanic rocks, namely the Kawabara Volcanic Member, overlying a basal conglomerate of the Tottori Group (the Koge Conglomerate Member) [4, 5]. The Iwami Formation is subdivided into the following four members: the Moroga Conglomerate, Fuganji Mudstone, Oda Andesite, and Aragane Pyroclastic Members in ascending order [4, 5]. We performed paleomagnetic samplings on the Kawabara Volcanic Member of the Yazu Formation and on the Moroga Conglomerate and Fuganji Mudstone Members of the lower part of the Iwami Formation in the eastern area of Tottori Prefecture (**Figure 2**). The Kawabara Member is composed mainly of andesite lavas and andesitic to dacitic pyroclastics and the Moroga Member consists of alternating beds of conglomerate and sandstone [4, 5]. Abundant molluscan fossils of the Kadonosawa Fauna have been found from the Moroga Member [29]. The Fuganji Member is made mainly of black mudstone deposited in deep marine environment. Matsumoto and Seto [30] found large foraminiferal fossils identical with *Operculina complanata japonica* from the Fuganji Member, and they correlated the horizon with the fossils to the Blow [20]'s planktonic foraminiferal zones from N8 to the base of N9.

In the Yakuno-Wadayama area, we collected samples from the Toyooka Formation at 16 sites (**Figure 2**): dacitic pyroclastic rocks and andesite lavas in the lower part of the formation at six sites, and in the upper part, volcanic sand, tuffs, and mudstones at nine sites and andesite lava at one site. In the Tottori area, paleomagnetic samples were obtained from the Tottori Group at 17 sites (**Figure 2**): mudstones and tuffs in the Fuganji Member at 10 sites, andesite lava in the Moroga Member at one site, and dacitic pyroclastic deposits and andesite lavas in the Kawabara Member at six sites. Paleomagnetic samplings were carried out by using a gasoline-powered core drill or by hand sampling. Three to ten cores or block samples oriented with a magnetic compass were collected at each site. Two or more cylindrical specimens of paleomagnetic standard size (24 mm in diameter and 22 mm in height) were prepared for each sample. Tilting values of strata were measured at two to eight points in the sampling sites, and mean values in the sites were adopted for tilt correction. Tilting data from dacitic pyroclastic layer intercalating in andesite lava units at WD-1 were used for tilt corrections for four sites of andesite lavas (WD-2, 3, 4, 5) because we did not find any layers in the lava units for measuring the tilting of the lava units.

3. Paleomagnetic analyses

3.1. Experiments

The stability of natural remanent magnetization (NRM) was accessed by progressive thermal and alternating field (AF) demagnetization experiments. The NRM of each specimen was measured with a superconducting rock magnetometer (model 760R of 2G Enterprises) or a spinner magnetometer (model SMD-85 of Natsuhara Giken). Thermal demagnetization was performed in air using an electric furnace with in a four-layer μ-metal magnetic shield. The internal residual field in the furnace is less than 10 nT. AF demagnetization was performed using a 2G AF demagnetizer with a three-axis tumbler system.

Two specimens from each site were subjected to the progressive thermal and AF demagnetization experiments, respectively. When the pilot specimens of a site showed linear trends of the vector endpoints decaying the origin of the orthogonal vector demagnetization diagram [31], remaining specimens of the site were demagnetized progressively mainly by thermal method. AF demagnetization was used on the remaining specimens if the pilot AF and thermal demagnetization results provided similar stable components and AF method appeared to be more effective to isolate the components. The direction of the component displaying as a linear trend on the diagrams was determined by using the principal component analysis [32]. The determined direction with a maximum angular deviation less than 5° was adopted. The component showing the linear trend toward the origin was regarded as a characteristic remanent magnetization (ChRM). The best-fit line for the linear trend toward the origin was anchored on the diagram for determining the direction of ChRM.

Site-mean directions of ChRMs and associated statistical parameters were calculated after Fisher [33]. Site mean directions with α_{95} less than 20° were regarded as reliable means of ChRMs and were adopted in the further consideration.

3.2. Demagnetization results

Figure 3 shows typical demagnetization behaviors of progressive demagnetization experiments. In samples from 17 among 19 sites of mudstone, tuff, and volcanic sand, low-stability components with northerly declination and positive inclination were observed generally below 200–300°C and/or 10–20 mT, which are probably viscous overprints of the recent geomagnetic field direction. NRMs of samples at the remaining two sites were unstable at lower demagnetization steps in both thermal and AF methods. After removal of the low-stability components, ChRMs were isolated below about 400–480°C and/or 30–40 mT at 11 sites, followed by erratic behaviors of magnetization in higher demagnetization levels (**Figure 3a–c**), while no stable component was found in samples of three sites. ChRMs were observed in the demagnetization levels up to 560–600°C at two sites of tuff (YK-9 and TR-9: **Figure 3d** and **e**). Mudstone samples of WD-6 provided two stable components below about 360°C: one with northeasterly declination and positive inclination below about 240°C and the other with southwesterly declination and negative inclination between 240 and 360°C. After removal of the two components, ChRMs in samples of WD-6 were isolated between about 360 and 480°C.

Samples from six sites of andesite lavas provided ChRMs above 400–500°C and/or about 20 mT after removals of the low-stability components regarded as the viscous overprint of the recent geomagnetic field direction below about 300°C and/or 15 mT or removals of considerable overlaps of the low-stability components with ChRMs up to about 400°C and/or 30–40 mT (**Figure 3f**). The ChRMs in samples of WD-16 were isolated by AF methods more effectively.

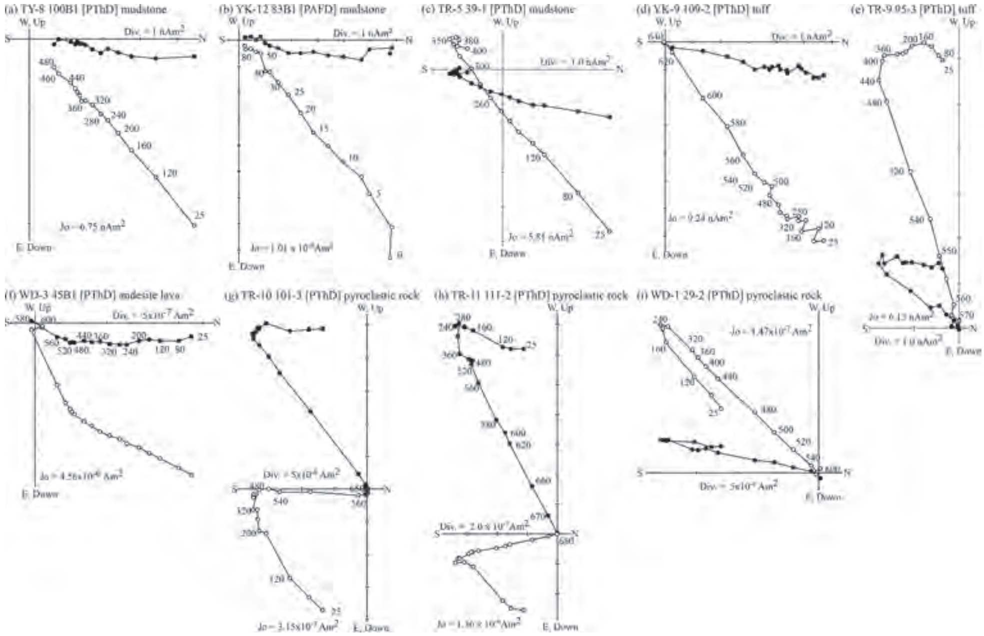

Figure 3. Typical results of progressive demagnetization experiments plotted on orthogonal vector demagnetization diagrams. Solid (open) symbols indicate projections of vector end-points on horizontal (vertical) planes in *in situ* coordinates. PThD: progressive thermal demagnetization. PAFD: progressive alternating field demagnetization.

Samples from six sites of pyroclastic rocks also showed the low-stability components below about 300°C and 15 mT (**Figure 3g–i**). The overlaps of the low-stability components with the higher stability components were also observed up to 400–500°C and 40 mT or more in four sites (TR-10, 11, 14 and 15: **Figures 3g** and **h**). At higher demagnetization steps, samples of four sites provided ChRMs below about 560°C for WD-1 (**Figure 3i**) and below 630–680°C for TR-11, 14, and 15 (**Figure 3h**). AF methods were not effective to isolate the ChRMs of TR-11, 14, and 15 because of high coercivity of the ChRMs: samples of the three sites were remained about 40–70% of initial intensity of NRM after AF demagnetization at 100 mT. Samples of TR-10 showed stable components shown as straight lines decaying not toward the origin on the demagnetization diagrams between 520 and 560°C before unstable magnetic behaviors in the higher demagnetization steps (**Figure 3g**). The directions of the stable components form TR-10 were close to those of ChRMs from TR-11 and14 as mentioned later.

3.3. Characteristic directions

Site mean directions of ChRMs with α_{95} less than 20° were obtained from seven sites of sedimentary rocks in the upper Toyooka Formation of the Hokutan Group (**Table 1** and **Figure 4**). The *in situ* directions with north declination and normal polarity are close to the directions of the present geomagnetic field and the geocentric axial dipole field (**Figure 4**) although the

Site	Locality		Lith	n/N	Demagnetization level		In situ		Tilt corrected		α_{95}	*k*	Bedding
	Lon (E)	**Lat (N)**					**D (°)**	**I (°)**	**D (°)**	**I (°)**			**strike, dip**
Hokutan Group													
Toyooka Formation (upper)													
YK-6	134°56′12″	35°24′07″	m	10/10	T	320–480°C	−4.8	49.4	−6.8	57.3	4.2	131.9	N70.7°W, 8°S
WD-6	134°55′59″	35°24′36″	t	9/10	T	360–500°C	−4.7	60.8	−15.4	70.8	6.4	65.6	N59.7°W, 11°S
YK-9	134°56′13″	35°24′12″	t	9/10	T	360–580°C	−2.5	49.5	−17.5	48.4	4.1	159.4	N9.3°E, 13°W
YK-7B	134°56′16″	35°24′11″	t	10/10	T	320–480°C	11.9	58.9	9.1	60.0	5.6	75.0	N9.7°W, 2°W
YK-7C	134°56′16″	35°24′11″	t	4/10	T	300–460°C	−1.3	57.9	−3.9	59.1	9.5	94.1	N25.7°W, 2°W
YK-8	134°56′23″	35°24′14″	m	9/10	T	320–480°C	0.3	52.6	−8.8	54.5	3.9	170.9	N5.7°W, 7°W
YK-12	134°56′25″	35°24′15″	m	10/10	A	15–40 mT	1.5	44.4	−3.2	48.5	3.6	179.1	N28.7°W, 6°W
		MEAN		*7*	*in-situ*		*−0.1*	*53.6*			*5.1*	*140.4*	
					tilt corrected				*−6.6*	*57.2*	*6.7*	*81.0*	
Toyooka Formation (lower)													
WD-2	134°55′53″	35°24′37″	al	10/10	T	480–570°C	43.2	52.1	48.1	49.2	5.5	77.2	N24.3°E, 5°E (*2)
WD-3	134°55′42″	35°24′41″	al	8/8	T	520–560°C	25.9	64.7	35.4	62.9	7.5	55.0	N24.3°E, 5°E (*2)
WD-4	134°55′32″	35°24′42″	al	10/10	T	320–600°C	17.2	47.4	22.5	46.5	4.7	105.5	N24.3°E, 5°E (*2)
WD-1	134°55′21″	35°24′48″	dp	4/4	T	280–550°C	−173.9	−44.5	−169.0	-44.6	2.5	1341.3	N24.3°E, 5°E
WD-5	134°55′24″	35°24′44″	al	3/3	T	360–560°C	−179.5	−50.6	−173.4	−51.1	5.8	452.5	N24.3°E, 5°E (*2)
		MEAN		*5*	*in-situ*		*17.5*	*52.8*			*12.4*	*39.2*	
					tilt corrected				*23.8*	*51.9*	*12.4*	*39.2*	

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Site	Locality		Lith	n/N	Demagnetization level		In situ		Tilt corrected		α_{95}	*k*	Bedding
	Lon (E)	**Lat (N)**					**D (°)**	**I (°)**	**D (°)**	**I (°)**			**strike, dip**
Tottori Group													
Fuganji Mudstone Member													
TR-6M	134°23′40″	35°26′39″	m	6/9	T	200–400°C	11.0	71.6	15.3	55.7	11.7	33.8	N54.7°W, 16°N
TR-7	134°22′54″	35°26′45″	m	8/8	T	200–320°C	−155.3	−46.8	−161.2	−43.0	2.6	452.8	N69.3°E, 7°N
TR-9	134°22′22″	35°26′45″	t	7/10	T	440–570°C	−144.3	−61.9	−144.8	−50.9	7.5	66.0	N41.7°W, 11°E
TR-5	134°28′44″	35°21′15″	m	4/8	T	350–400°C	−179.9	−51.8	−178.8	−46.9	19.9	22.3	N63.7°W, 5°N
		MEAN		*4*	*in-situ*		*17.8*	*58.7*			*15.8*	*34.8*	
					tilt corrected				*17.4*	*49.8*	*12.1*	*58.6*	
Moroga Conglomerate Member													
TR-1	134°24′08″	35°23′22″	al	8/8	T	400–570°C	−85.3	−32.8	−93.7	−25.0	6.5	72.8	N47.7°W, 17°N
Kawabara Volcanic Member													
TR-10 [*1]	134°22′07″	35°26′36″	dp	10/10	T	520–580°C	−136.0	−0.5	−137.0	12.9	1.7	763.5	N1.3°E, 16°E
TR-11	134°22′02″	35°26′33″	dp	8/8	T	480–670°C	−124.9	6.2	−123.3	14.5	2.2	589.9	N65.7°W, 12°N
TR-14	134°21′56″	35°26′32″	dp	8/8	T	440–660°C	−119.6	0.1	−119.2	13.7	2.2	659.7	N28.7°W, 14°E
		MEAN		*3*	*in-situ*		*−126.8*	*1.9*			*14.0*	*78.5*	
					tilt corrected				*−126.4*	*13.8*	*14.0*	*78.9*	
TR-16	134°22′14″	35°24′33″	al	6/8	A	25–60 mT	−101.5	−39.9	−111.4	−49.8	11.6	34.2	N43.3°E, 14°E

Note: lith: lithology, m: mudstone, t: tuff, al: andesite lava, dp: dacitic pyroclastic rock. n/N: the number of samples used in a site mean calculation (n) and samples corrected at the sit (N), demagnetization: demagnetization levels of thermal (T) or alternating-field (A) methods showing the characteristic magnetic components, D and I: declination and inclination of the mean, respectively, α_{95}: the radius of the 95% circle of confidence around the site mean direction, *k*: Fisher precision parameter. Directions of declination and strike of bedding are corrected by the local geomagnetic declination (7.3°W) at each site. *1: the direction of TR-10 is a mean direction of stable components decaying not toward the origin (see in the text). *2: bedding data is that of WD-1.

Table 1. Site-mean directions of characteristic remanent components obtained from Hokutan and Tottori Groups.

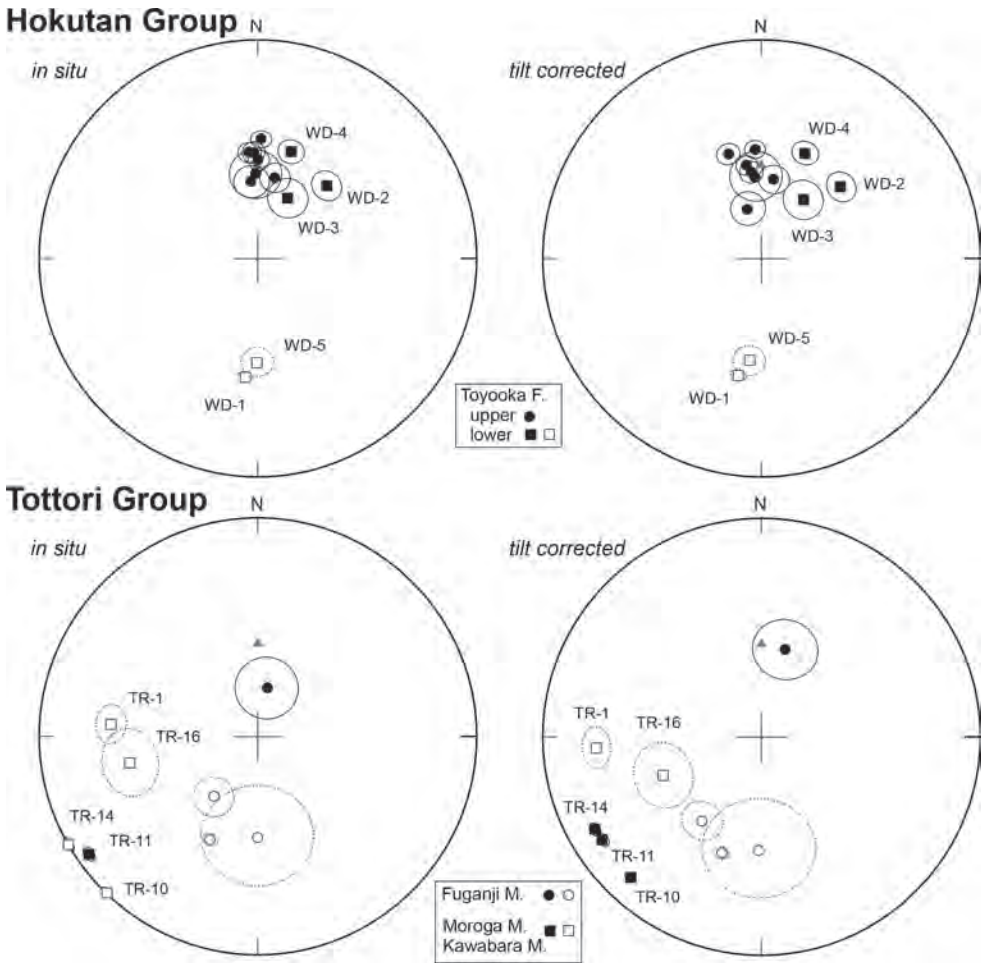

Figure 4. Site-mean directions of characteristic remanent magnetizations with 95% confidence circles plotted on equal-area nets before (left) and after (right) tilt corrections. Solid (open) symbols are on the lower (upper) hemisphere. A solid triangle on each net represents the direction of the geocentric axial dipole field expected at each sampling area.

low-stability components, which are regarded as viscous overprints of the recent geomagnetic field direction, were erased by the demagnetization experiments. Tilt-corrected directions do not show better grouping than the *in situ* directions (**Table 1**): α_{95} and the precision parameter are 5.1° and 140.4 for a mean of the *in situ* directions, while 6.7° and 81.0 for that of the tilt-corrected. It is probably inferred that the viscous overprints of the recent geomagnetic filed direction were not demagnetized perfectly and/or that tilt corrections were not effective because directional differences in tilting among the sites were little. The ChRMs of the sediment sites cannot be regarded as primary magnetic components acquired before tilting of the strata.

Site mean directions were obtained from five sites of volcanic sequence in the lower Toyooka Formation (**Table 1** and **Figure 4**). We performed tilt correction on the five *in situ* directions by tilting data from dacitic pyroclastic layer interbedded in andesite lava units at WD-1. Tilt-corrected directions show an antipodal relationship with a NNE-SSW trend approximately, and the lower two sites in the volcanic sequence are negative polarity while the upper three sites are positive polarity. A mean of the five tilt-corrected directions is D = 23.8°, I = 51.9°, and α_{95} = 12.4°, which is regarded as a paleomagnetic direction of the lower Toyooka Formation in the further consideration. Confidence limits on D and I associated with the value of α_{95}, namely Δ□ and ΔI, are 20.4° (Δ□ = $\sin^{1}[\sin \alpha_{95}/\cos I]$) and 12.4° (ΔI = α_{95}), respectively. The difference between the mean direction and the geocentric axial dipole field (GADF) direction expected at the Yakuno-Wadayama area (D_G = 0° and I_G = 54.9°) are D-D_G = 23.8° ± 20.4° in declination and I-I_G = −4.9° ± 12.4° in inclination. The mean direction is found to show a significant CW deflection in declination.

From the upper part of the Tottori Group, site mean directions are obtained at four sites of the Fuganji Mudstone Member, showing an antipodal relationship with a N-S trend (**Table 1**, **Figure 4**). The directions are grouped more tightly after tilt correction than in *in situ* coordinate: α_{95} and the precision parameter change from 15.1 to 12.1° and from 34.8 to 58.6, respectively (**Table 1**). The ChRMs from the four sites are considered as the components acquired before tilting. The geomagnetic polarity is negative for TR-5, 7, and 9 in the lower horizons of the Fuganji Member and positive for TR-6M in the upper horizon. A mean of the four tilt-corrected directions, D = 17.4°, I = 49.8°, and α_{95} = 12.1°, is regarded as a paleomagnetic direction of the Fuganji Member. Δ□ and ΔI are 19.0° and 12.1°, respectively. The difference between the paleomagnetic direction and the expected direction of the GADF at the Tottori area (D_G = 0° and I_G = 54.9°) is 17.4° ± 19.0° in declination and 5.1° ± 12.1° in inclination, indicating no statistical significance in the difference.

From the lower part of the Tottori Group, site mean directions of ChRMs were obtained at one site (TR-1) of andesite lava in the Moroga Conglomerate Member and at two sites of dacitic pyroclastic rocks (TR-11 and 14) and one site of andesite lava (TR-16) in the Kawabara Volcanic Member (**Table 1**, **Figure 4**). *In situ* and tilt-corrected directions of TR-1 and 16 show west-southwesterly declination with negative inclination, while those of TR-11 and 14 are characterized by very shallow inclination with southwesterly declination. The directions of TR-11 and 14 are similar to a mean direction of the stable components at TR-10 of pyroclastics (**Figure 4**). Mean directions from the three sites of pyroclastics before and after tilt correction have same values of α_{95} and precision parameter (**Table 1**). Based on the demagnetization results, the ChRMs of TR-11 and 14 are carried by magnetite and hematite and those of TR-10 are carried by magnetite. The stable components of the three sites seem to be characteristic components of pyroclastic rocks in the horizons of TR-10, 11, and 14, which are close stratigraphically (**Figure 2**) and might have been acquired at the formation time of the pyroclastics although the fold test is not positive for the directions of the three sites. Tilt-corrected directions of the three sites appear to be anomalous, possibly implying that the characteristic components are regarded as a record of anomalous direction of the geomagnetic field during a geomagnetic excursion or polarity change. A mean calculation and fold test for the only two directions of TR-1 and 16 are not meaningful. The stable ChRMs of the sites are considered to be free from the viscous overprint of the recent geomagnetic field based on the demagnetization results as mention above. Tilt-corrected directions of the two sites with negative inclinations are likely to indicate reverse polarities of the horizons (**Figure 2**).

4. Discussion

The paleomagnetic data from the Miocene sequences in the Tottori and Yakuno-Wadayama areas, the eastern part of the San'in district, imply a CW rotational motion after the volcanic activity prior to the marine transgression and no significant rotation after the formation of the marine sedimentary sequences for the eastern San'in district.

In the Yakuno-Wadayama area, a paleomagnetic direction was determined for the volcanic sequence in the lower Toyooka Formation and shows a significant CW deflection in declination (23.8° ± 20.4°: **Table 2**). A CW rotation of 24° is implied for this area after the volcanic activities forming the lower Toyooka Formation. Sakamoto [34] reported paleomagnetic data from the Toyooka Formation. Site-mean directions were obtained at three sites of sedimentary rocks (mudstone, sandstone, and tuff) and one site of volcanic rocks (rhyolite) showing horizontal bedding (**Figure 5**). An overall mean of the four sites (D = 4.6°, I = 46.4°, and α_{95} = 25.1°: **Table 2**) shows no significant deflection from the direction of the geocentric axial dipole field (GADF) expected at this area (D = 4.6° ± 38.0°), indicating no rotational motion after the formation of the Toyooka Formation [34]. Although sampling horizons of Sakamoto [34] in the Toyooka Formation are unknown, it is suggested that no significant rotational movement occurred after the formation of the sedimentary sequence in the upper Toyooka Formation. In the Tottori area, a paleomagnetic direction from the Fuganji Member shows a slightly CW deflection in declination relative to the expected direction of the GADF, but the deflection is not significant statistically (17.4° ± 19.0°: **Table 2**). It is indicated that the Tottori area has suffered no significant rotational motion after the formation of the Fuganji Member associated with the marine transgression. Two tilt-corrected directions from the Moroga and Kawabara Members show large CW deflections in declination (**Figure 4**). The CW deflected directions may also imply a possibility to represent a CW rotational motion before the formation of the marine sequence in the eastern San'in district.

Paleomagnetic and magnetobiostratigraphic investigations with radiometric age controls have been performed systematically on the Miocene sequences in the Hokuriku district (**Figure 1**), namely the Hokuriku Group and its corresponding strata, by Itoh and his corroborators [14, 35–37]. Itoh and Watanabe [36] revealed a magnetostratigraphy of the Yatsuo Group in the Yatsuo area (**Figures 1** and **5**), which is the lower unit of the Hokuriku Group. The Yatsuo Group consists of the Nirehara, Iwaine, Iozen, Kurosedani and Higashibessho Formations in ascending order [3] (**Figure 5**). The Kurosedani and Higashibessho Formations are marine sequences deposited under the marine transgression and subsequent rapid subsidence of sedimentary basins, and fossils of the Kadonosawa Fauna are found in the Kurosedani Formation [3]. A reverse polarity zone in the Iozen, Kurosedani and Higashibessho Formations is assigned to C5Br of the standard geomagnetic polarity scale of Berggren et al. [38] (**Figure 5** [36]). The age

Miocene sequences	n	D (°)	I (°)	α_{95} (°)	ΔD	Reference
Eastern San'in						
Hokutan Group						
Toyooka F.	4	4.6	46.4	25.1	38.0	[32]
lower part of Toyooka F.	5	23.8	51.9	12.4	20.4	This study
Tottori Group						
Fuganji Mudstone Member	4	17.4	49.8	12.1	19.0	This study
Hokuriku						
Hokuriku Group						
[Yastuo]						
Higashibessho F.	6	−4.5	56.4	10.0	18.3	[36]
Kurosedani F.	8	3.6	45.4	6.2	8.3	[35, 39, 40]
Iozen/Iwaine/Nirehara F.	6	20.9	49.4	6.7	10.3	[39, 40]
[Kanazawa-Iozen]						
Sunagozaka/Nanamagari F.	7	23.5	50.2	11.4	18.0	[14, 36]
Iozen F.	11	36.4	51.6	12.1	19.7	[34, 35]
Mt. Wasso Rhyolite	5	49.9	56.6	12.2	22.6	[13]
[Daishoji]						
Kasanomisaki F.	3	5.1	54.9	9.7	17.0	[34]
Kawaminami F.	4	33.5	52.8	4.4	7.3	[34]
Central San'in						
Iwami Group						
Omori F.	18	0.0	55.9	8.9	16.0	[8]
Kawai F.	8	38.4	39.8	15.1	19.8	[8]
Hata F.	6	69.4	48.2	14.9	22.7	[48]
Hata F.	5	3.5	42.9	9.9	13.6	[50]
Sada F.	6	52.5	43.2	13.1	18.1	[50]

Note: n: number of sites for calculating a mean, D/I: mean declination/inclination, α_{95}: radius of 95% confidence limit for a mean. ΔD is a confidence limit on D, estimated using the following equation: $\Delta D = \sin^{-1}[\sin \alpha_{95}/\cos I]$.

Table 2. Paleomagnetic directions from Miocene sequences in the Hokuriku and San'in districts.

range of C5Br is between 15.974 and 15.160 Ma based on Geological Time Scale (GTS) 2012 [39]. A horizon with normal polarity at the uppermost part of the Higashibessho Formation and a normal polarity zone in the lowermost part of the Iozen Formation and the Iwaine Formation of volcanic sequences is assigned to C5Bn and C5Cn, respectively [36]. The Nirehara Formation shows reverse polarity and is assigned to C5Cr [40].

In the Hokuriku district, paleomagnetic directions from the Kurosedani Formation and its corresponding strata [14, 35–37, 40, 41] show different amounts of CW deflection in declination (**Table 2**, **Figure 5**): the Sunagozaka/Nanamagari Formations at the Kanazawa-Iozen area and the Kasanomisaki Formation at the Daishoji area show CW deflections of 23.5° ± 18.0° and 33.5° ± 7.3°, respectively, while the Kurosedani Formation at the Yatsuo area shows no significant deflection (3.6° ± 8.8°). The difference in CW deflection among paleomagnetic declinations of the Kurosedani Formation and its corresponding strata has been attributed to the differential rotation in the eastern part of SW Japan caused by a collision of the Izu-Bonin arc just after the CW rotation of SW Japan as a coherent block [35, 42]. Itoh et al. [37] revealed that paleomagnetic directions from the strata assigned to NPD-4A zone of diatom biostratigraphy [43], namely the Higashibessho Formation at the Yatsuo area and the Kasanomisaki Formation at the Daishoji area (**Figure 1**), show no deflection in declination while CW deflections in paleomagnetic declinations are observed in the strata assigned to the diatom-biostratigraphic NPD-3A zone or the foraminiferal zone of N8 and older strata (**Table 2**, **Figure 5**). It is suggested that the CW rotation of SW Japan occurred at the latest early Miocene assigned to the diatom-biostratigraphic zone of NPD-3B [37]. Itoh and Kitada [14] revealed a successive decrease in CW deflection of paleomagnetic declinations among paleomagnetic directions from the Mt. Wasso Rhyolite of about 20 Ma (D =49.9° ± 22.6°), the Iozen Formation of volcanic sequences (D = 36.4° ± 19.7°) and the Sunagozaka/Nanamagari Formations in the Kanazawa-Iozen area (**Table 2**, **Figures 1** and **5**), and suggested that the CW rotation of SW Japan may have commenced in the early Miocene and that the rotation was accelerated after the initial stage of marine transgression.

In this study, samples of the Moroga Member and the lower part of the Fuganji Member at the Tottori area show reverse polarities (**Figures 2** and **5**). The Moroga Member includes fossils of the Kadonosawa Fauna. The Fuganji Member is assigned to the planktonic foraminiferal zone of N8 and the base of N9 [30]. Compared with the magnetostratigraphy of the Yatsuo Group [36], it is suggested that the reverse polarity horizons in the Moroga and Fuganji Members are probably correlated to C5Br and that a horizon with normal polarity at the upper part of the Fuganji Member (TR-6M) is possibly assigned to C5Bn. A reverse polarity of TR-16 below the horizons with transitional polarities (TR-10, 11 and 14) in the Kawabara Member (**Figure 2**) might have been correlated to one of reverse polarity subchrons in C5Cn or C5Cr. According to the lithology of the Toyooka Formation at the Yakuno-Wadayama area, sedimentary sequences in the upper part, which include fossils of the Kadonosawa Fauna at its basal part, and the volcanic sequences in the lower part are considered to be correlated to the Kurosedani Formation and the underlying volcanic sequences (the Iozen Formation and older volcanic units), respectively, in the Hokuriku Group. Horizons of normal and reverse polarities in the volcanic sequences at the lower Toyooka Formation (**Figure 2**) may be correlated to a normal polarity zone in the Iozen and Iwaine Formations, assigned to C5Cn [40] and to a reversal polarity one in the Nirehara Formation (C5Cr) at the Yatsuo area or possibly one of reverse polarity subchrons in C5Cn, respectively. According to the above-mentioned magnetostratigraphic correlation, it is implied that the CW rotation of 24° inferred for the eastern San'in district occurred at around 16 Ma after the early Miocene volcanic activity and before the middle Miocene marine transgression in the whole process of the CW rotation of SW Japan in Miocene time.

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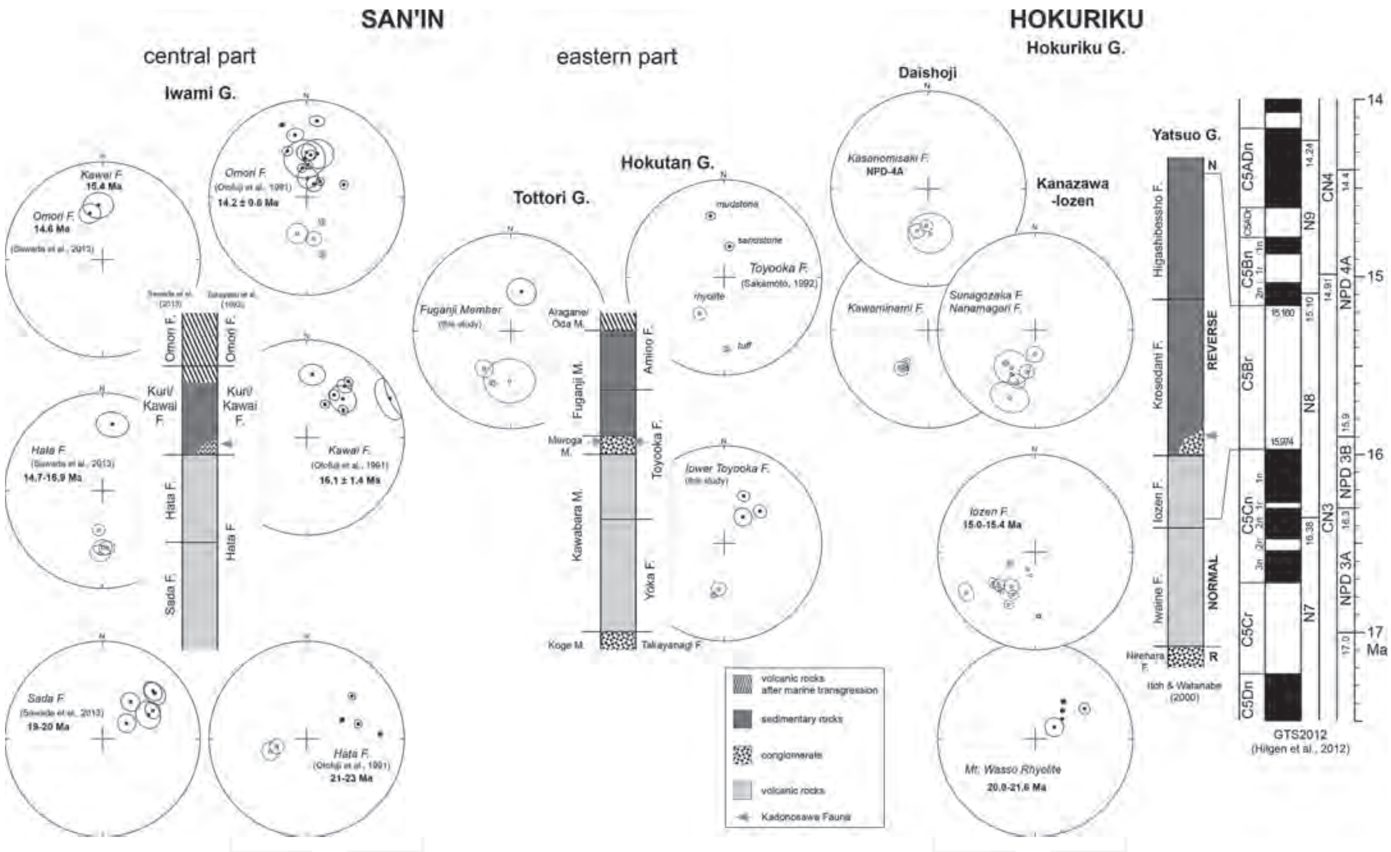

Figure 5. Comparison of paleomagnetic directions from Miocene sequences in the San'in and Hokuriku districts, listed in **Table 2**. Solid (open) symbols on equal-area nets are on the lower (upper) hemisphere. The geomagnetic polarity time scale and biostratigraphic zonations of planktonic foraminifera and calcareous nannofossils are after Geological time scale 2012 [39]. Ages for NPD zones [43] of diatom biostratigraphy are referred to Refs. [52, 53]. The generalized columnar section and magnetostratigraphy of the Yatsuo Group are modified from Ref. [36]. The generalized columnar section of the Hokutan and Tottori Groups is modified from Refs. [2, 29], and that of the Iwami Group is modified from Refs. [6, 51].

A paleomagnetic direction of the Fuganji Member shows no significant deflection in declination, implying that a rotational motion related to the CW rotation of SW Japan ceased before the formation of the Fuganji Member related to the marine transgression in the eastern San'in district. If so, it is also inferred that the horizons providing paleomagnetic data in the Fuganji Member, assigned to C5Br-C5Bn, may be correlated to the Higashibessho Formation and its corresponding strata of the Hokuriku Group assigned to the diatom zone of NPD-4A. A CW deflected site mean direction with reverse polarity from the Moroga Member (TR-1: **Figure 4**), which includes fossils of the Kadonosawa Fauna, may imply a possibility that a CW rotation occurred after the initiation of the marine transgression in the eastern San'in district. More detailed paleomagnetic investigations on the Fuganji Member, as well as the upper Toyooka Formation, may detect a rotational motion at the initial stage of the marine transgression in the eastern San'in district as suggested in the Hokuriku district [14].

In the central area of the San'in district (**Figure 1**), the Miocene sequences of the Iwami Group consist of the Hata, Kawai/Kuri, and Omori Formations in ascending order [6, 44] (**Figure 5**). The marine transgression is recorded in the Kawai/Kuri Formations, and fossils of the Kadonosawa Fauna were reported from the Kawai Formation [45, 46]. Hayashi et al. [47] found planktonic foraminiferal fossils and calcareous microfossils assigned to N8 and CN3 zones, respectively, from the Kuri Formation, and the overlap age of the two zones ranges between 16.38 and 15.10 Ma based on GTS2012 [39]. Otofuji and Matsuda [48] estimated a total amount of CW rotation of SW Japan of 44–47° with respect to East Asia associated with the opening of Japan Sea since about 20 Ma based on Cretaceous to Miocene paleomagnetic data from the western and central parts of the San'in district, including a CW deflected paleomagnetic direction from the Hata Formation (D = 69.4° ± 22.7°: **Table 2**) of 23–21 Ma [49]. Otofuji et al. [8] performed paleomagnetic and K-Ar dating analyses on volcanic rocks of the Kawai/Kuri and Omori Formations (**Table 2**, **Figure 5**): a paleomagnetic direction of the Kawai Formation with a mean age of 16.1 ± 1.4 Ma shows a CW-deflected declination (38.4 ± 19.8°), while that of the Omori Formation with a mean age of 14.2 ± 0.6 Ma has no significant deflection in declination (0.0 ± 16.0°). Otofuji et al. [8] suggest that more than 80% of the CW rotation of SW Japan occurred between 16 and 14 Ma.

All site mean directions from lavas of the Kawai Formation [8] have normal polarities (**Figure 5**), which may be correlated to the normal polarity zone in the Iozen and Iwaine Formations, assigned to C5Bn, based on the magnetostratigraphy of the Hokuriku Group [36]. A paleomagnetic direction of the volcanic sequences in the lower Toyooka Formation, which is also correlated to the Iozen and Iwaine Formations as mentioned above, has a CW deflected declination of 23.8° ± 20.4°. The deflected declination implies a CW rotation of 24° for the eastern San'in district. The rotation angle for the eastern San'in district is smaller than the total amount of the CW rotation for Southwest Japan estimated by Otofuji and Matsuda [48]. The amount of the CW deflection from the lower Toyooka Formation appears to be also smaller than that of the Kawai Formation, which might have inferred a differential rotation for the eastern San'in district during the CW rotation of SW Japan. For estimating the difference in declination between the Kawai Formation and the lower Toyooka Formation, expected directions at the representative point of SW Japan (35°N and 134°E) are calculated from the

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paleomagnetic directions of the two formations as follows: D = 38.5°, I = 40.7°, α_{95} = 15.1°, and ΔD = 20.1° for the Kawai Formation, and D = 23.9°, I = 51.9°, α_{95} = 12.3°, and ΔD = 20.2° for the lower Toyooka Formation. The difference in declination between the Kawai Formation and the lower Toyooka Formation (14.8° ± 28.5°) estimated as defined by Beck [50] is not statistically significant. It is probably implied that the CW rotation for the eastern San'in district at around 16 Ma represents a rotational motion of SW Japan at the climax stage or the final stage in the whole process of the CW rotation related to the Japan Sea opening as suggested by Otofuji et al. [8].

Based on the above-mentioned paleomagnetic data from the Miocene sequences in the San'in and Hokuriku districts, it is pointed out that magnetic polarities of the strata including fossils of the Kadonosawa Fauna are different among the Miocene sequences: the strata in the eastern San'in and Hokuriku districts, namely the Moroga Member and the Kurosedani Formation, show reverse polarities assigned to C5Br, while the Kawai Formation in the central San'in district has normal polarity probably assigned to C5Cn. It may be inferred that the marine transgression in the central San'in district occurred before the CW rotation of SW Japan, preceding the marine transgression in the eastern San'in and Hokuriku districts.

On the other hand, according to results of geochronological and paleomagnetic investigations of Sawada et al. [51] in the central San'in district (**Figure 5**), it is implied that a CW rotational motion in the central San'in district at about 16 Ma [51] ceased before the formation of the Kawai/Kuri Formations related to the marine transgression. Sawada et al. [51] indicated that a paleomagnetic direction of the Sada Formation with K-Ar ages of 20–19 Ma, which has been previously recognized as the Kawai Formation, shows a large CW deflection in declination (52.5° ± 18.1°: **Table 2** and **Figure 5**), while a paleomagnetic direction of the Hata Formation, of which K-Ar ages range between 16.9 and 14.7 Ma, has no significant deflected paleomagnetic declination (9.0° ± 12.0°). Site-mean directions from the Kawai Formation of 15.4° ± 0.6° Ma and the Omori Formation of 14.6° ± 0.8° Ma also show no deflected declinations with normal polarities (**Figure 5**). According to the results of Sawada et al. [51], the Kawai Formation with normal magnetic polarity may be assigned to C5Bn or younger normal magnetic chron. More detailed magnetostratigraphic investigations on the Miocene sequence in the central San'in district may be still indispensable in order to clarify the aspect of the Miocene marine transgression in SW Japan related to Japan Sea opening accompanied with the CW rotation of Southwest Japan.

5. Conclusions

We performed paleomagnetic investigations on volcanic and sedimentary rocks at 33 sites of Miocene sequences at the eastern part of the San'in district in SW Japan, namely the Tottori and Hokutan Group, and suggest the following conclusions:

1. Two paleomagnetic directions were determined for the Miocene sequences in the eastern San'in district as follows:

Volcanic sequence of the lower Toyooka Formation in the Hokutan Group: D = 23.8°, I = 51.9°, and α_{95} = 12.4°.

Sediments of the Fuganji Mudstone Member in the Tottori Group: D = 17.4°, I = 49.8°, and α_{95} = 12.1°.

The paleomagnetic direction of the lower Toyooka Formation has an easterly-deflected declination (D = 23.8° ± 20.4°), while that of the Fuganji Member shows no significant deflection in declination (D = 17.4° ± 19.0°).

2. Based on the comparison of lithology, magnetostratigraphy, and geochronological data in the Miocene sequences between the eastern San'in and Hokuriku districts, magnetic polarities in the lower Toyooka Formation and Fuganji Member are probably assigned to C5Cn and C5Br-C5Bn, respectively.

3. It is suggested that the eastern San'in district suffered a CW rotation of 24° at around 16 Ma after the early Miocene volcanic activity and before the middle Miocene marine transgression, which is attributed to the rotational motion at the climax stage in the whole process of the CW rotation of the SW Japan block related to the formation of the Japan Sea back-arc basin in Miocene time.

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Author details

Naoto Ishikawa[1]*, Takashi Suzuki[1] and Shiro Ishida[2]

*Address all correspondence to: ishikawa@gaia.h.kyoto-u.ac.jp

1 Graduate School of Human and Environment Studies, Kyoto University, Kyoto, Japan

2 Lake Biwa Museum, Siga, Japan

References

[1] Wadatsumi K, Matsumoto T. The stratigraphy of the Neogene formations in the northern Tazima—Study of the Neogene in the North-western part of the Kinki District—(Part 1). Journal of the Geological Society of Japan. 1958; **64**: 625-637 (in Japanese with English abstract).

http://dx.doi.org/10.5772/67960

[2] Wadatsumi K, Ikebe N, Matsumoto T. Correlation of the Neogene Formations of Northern Kinki, Southwest Japan—Studies of the Late Cenozoic Formations in Northern Kinki District, Part 3. Professor Susumu Matsushita Memorial Volume. 1966; 105-116 (in Japanese with English abstract).

[3] Hayakawa H, Takemura A. The Neogene system in the Yatsuo area, Toyama Prefecture, central Japan. Journal of the Geological Society of Japan. 1987; **93**: 717-732 (in Japanese with English abstract).

[4] Matsumoto T. Stratigraphy of the Miocene series in the area southeast of Tottori City, Tottori Prefecture, Southwest Japan. Journal of the Geological Society of Japan. 1986; **92**: 269-287 (in Japanese with English abstract).

[5] Matsumoto T. Stratigraphical study of the Miocene series in the eastern part of Tottori Prefecture, Southwest Japan. Journal of Science of the Hiroshima University. Series C. 1989; **9**:199-235.

[6] Takayasu K, Yamasaki H, Ueda T, Akagi S, Matsumoto T, Nomura R, Okada S, Sawada Y, Yamauchi S, Yoshitani A. Miocene stratigraphy and paleogeography of the San'in district, Southwest Japan. The Memoirs of the Geological Society of Japan. 1992; **37**: 97-116 (in Japanese with English abstract).

[7] Otofuji Y, Hayashida A, Torii M. When was the Japan Sea opened?: paleomagnetic evidence from Southwest Japan. In: Nasu N., Uyeda S., Kushiro I., Kobayashi K., Kagami H., editors. Formations of Active Ocean Margins: Terrapub; 1985. pp. 551-566.

[8] Otofuji Y, Itaya T, Matsuda T. Rapid rotation of southwest Japan-palaeomagnetism and K-Ar ages of Miocene volcanic rocks of southwest Japan. Geophysical Journal International. 1991; **105**: 397-405.

[9] Otofuji Y. Large tectonic movement of the Japan Arc in the late Cenozoic times inferred from paleomagnetism: review and synthesis. The Island Arc. 1996; **5**: 229-249.

[10] Hayashida A. Timing of rotational motion of Southweest Japan inferred from paleomagnetism of the Setouchi Miocene Series. Journal of Geomagnetism and Geoelectricity. 1986; **38**: 295-310.

[11] Nakajima T, Hayashi M, Nakagawa T. Two step motions of the clockwise rotation of Southwest Japan during the Miocene. Professor Shizuka Miura Memorial Volume. 1991; 105-119 (in Japanese with English abstract).

[12] Nakajima T, Sawada Y, Nakagawa T, Hayashi M, Itaya T. Paleomagnetic results and K-Ar dating on Miocene rocks in the northern part of Fukui Prefecture, Central Japan—with reference to the rotation of Southwest Japan. Journal of Mineralogy, Petrology and Economic Geology. 1990; **85**: 45-59 (in Japanese with English abstract).

[13] Itoh Y, Doshida S, Kitada K, Danhara T. Paleomagnetism and fission-track ages of the Mt. Wasso moonstone rhyolitic welded tuff in the Ishikawa Prefecture, central Japan. Bulletin of the Geological Survey of Japan. 2001; **52**: 573-579 (in Japanese with English abstract).

[14] Itoh Y, Kitada K. Early Miocene process in the eastern part of south-west Japan inferred from paleomagnetic studies. The Island Arc; 2003: **12**, 348-356.

[15] Otofuji Y, Matsuda T, Nohda S. Opening mode of the Japan Sea inferred from the paleomagnetism of the Japan Arc. Nature. 1985; **317**: 603-604.

[16] Oyama K. Studies of fossil molluskan biocoenosis, No. 1: biocoenological studies on the mangrove swamps, with descriptions of new species from Yatsuo Group. Reports, Geological Survey of Japan. 1950; **132**: 1-16.

[17] Chinzei K. Faunal succession and geographic distribution of Neogene molluscan faunas in Japan. In: Kotaka T, editors. Origin and Migration of the Japanese Cenozoic Mollusca. Paleontological Society of Japan. Special Papers. 1986; **29**: 17-32.

[18] Chinzei K. Opening of the Japan Sea and Marine Biogeography during the Miocene, Journal of Geomagnetism and Geoelectricity. 1986; **38**: 487-494.

[19] Chinzei K. Late Cenozoic zoogeography of the Sea of the Japan area, Episodes, 1991; **14**: 231-235.

[20] Blow WH. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: Bronnimann P, Renz H.H, editors. Proceedings of the First International Conference on Planktonic Microfossils. Vol. 1: EJ Brill Leiden; 1969. pp. 199-422.

[21] Yamada N, Saito E, Murata Y. Computer-Generated Geologic Map of Japan (scale 1:200,000), 1:2,000,000 Map Series 22, Geological Survey of Japan, 1990.

[22] Yamamoto T, Hoshizumi H. Stratigraphy of the Neogene system in the Tango Peninsula, eastern part of the San-in district, Southwest Japan, and associated Middle Miocene volcanism. Journal of the Geological Society of Japan. 1988; **94**: 769-781 (in Japanese with English abstract).

[23] Editorial Committee of Engineering Geological Maps of Hyogo Prefecture. Geology of Hyogo—Explanatory text of geological maps (scale 1:100,000) of Hyogo Prefecture, geological part—Hyogo Construction Technology Center, Kobe. 1996. 361p (in Japanese).

[24] Ishida S. "Era of Island Arc"—Geological history of Yakuno Town since Neogene. In: Yakuno Town History editorial board, editors. History of Yakuno Town, Volume 1, Natural Sciences and Folk Traditions. 2005. pp. 68-134 (in Japanese).

[25] Furuyama K, Sawada Y, Itaya T, Miyake Y, Inoue Y, Kotaki A. K-Ar ages of some volcanic rocks from the Yoka Formation, Miocene Hokutan Group, northern Kinki district. Earth Science (Chikyu Kagaku). 1997; **51**: 452-457 (in Japanese).

[26] Matsubara T. Miocene shallow marine molluscs from the Hokutan Group in the Tajima area, Hyogo Prefecture, southwest Japan. Bulletin of the Mizunami Fossil Museum. 2011; **37**: 51-113.

[27] Nakagawa T, Chiji M, Miura S. Miocene geology and planktonic foraminifers of the Uchiura area, Fukui Prefecture, central Japan. Journal of the Geological Society of Japan. 1985; **91**: 389-402 (in Japanese with English abstract).

[28] Tottori Green Tuff Research Group. Studies on stratigraphy and structures of Tottori Group, Lower and Middle Miocene strata, distributed in the southeast area of Tottori City, Southwest Japan. Monograph of the Association for the Geological Collaboration in Japan. 1989; **36**: 85-104.

[29] Uemura F, Sakamoto T, Yamada N. Geology of the Wakasa District, Scale 1:50,000 Quadrangle Series, Geological Survey of Japan. 1979. 91p (in Japanese with English abstract).

[30] Matsumoto T, Seto K. New occurrence of Operculina from the Tottori Group, and its biostratigraphical and paleozoogeographical significance. Geological Report of Shimane University. 1994; **13**: 47-56 (in Japanese with English abstract).

[31] Zijderveid JDA. A. C. demagnetization of rocks: Analysis of results. In: Collinson, DW, Creer KM, Runcorn SK, editors. Methods in Palaeomagnetism. Amsterdam: Elsevier; 1967, pp. 254-268.

[32] Kirschvink JL. The least-squares line and plane and analysis of paleomagnetic data. Geophysical Journal of the Royal Astronomical Society. 1980; **62**: 699-718.

[33] Fisher RA. Dispersion on a sphere. Proceedings of the Royal Society of London. Series A. 1953; **217**: 295-305.

[34] Sakamoto M. Lava block rotation around vertical axis inferred from remanence directions of Miocene Yoka Formation, Southwest Japan. Journal of Geomagnetism and Geoelectricity. 1992; **44**: 55-63.

[35] Itoh Y, Ito Y. Confined ductile deformation in the Japan arc inferred from paleomagnetic studies. Tectonophysics. 1989; **167**: 57-73.

[36] Itoh Y, Watanabe M. Refined magnetostratigraphy of the Early Miocene sequence in the Yatsuo area, central Japan. Bulletin of the Geological Survey of Japan. 2000; **51**: 37-45 (in Japanese with English abstract).

[37] Itoh Y, Yamamoto A, Iwano H, Danhara T, Watanabe M. Paleomagnetism and fission-track ages of the Miocene sequence in the Kanazawa and Iozen areas, central Japan. Bulletin of the Geological Survey of Japan. 2000; **51**: 495-504 (in Japanese with English abstract).

[38] Berggren WA, Kent DV, Swisher CC-III, Aubry MP. Geochronology, Time Scales and Global Stratigraphic Correlation. In: Bergrenn WA, Kent DV, Aurbry MP, Hardenbol J, editors. Society for Sedimentary Geology, Tulsa, Oklahoma. SEPM Special Publication No. 54, 1995. pp. 129-212.

[39] Hilgen FJ, Lourens LJ, Van Dam JA. The neogene period. In: Gradstein FM, Ogg JG, Schmitz MD, Ogg GM, editors. The Geologic Time Scale 2012, vol. 2, 2012. pp. 923-978.

[40] Itoh Y, Hayakawa H. Magnetostratigraphy of Neogne rocks around the Yatsuo area in Toyama Prefecture, Japan. Journal of the Geological Society of Japan. 1988; **94**: 515-525 (in Japanese with English abstract).

[41] Itoh Y, Hayakawa H. On the boundary of polarity chron C5B/C5C in the Neogene section of the Yatsuo area in Toyama Prefecture, Japan. Journal of the Geological Society of Japan. 1989; **95**: 133-136 (in Japanese with English abstract).

[42] Itoh Y. Differential rotation of the eastern part of southwest Japan inferred from paleomagnetism of Cretaceous and Neogene rocks. Journal of Geophysical Research. 1988; **95**: 3401-3411.

[43] Yanagisawa Y, Akiba F. Refined Neogene diatom biostratigraphy for the northwest Pacific around Japan, with an introduction of code numbers for selected diatom biohorizons. Journal of the Geological Society of Japan. 1998; **104**: 395-414.

[44] Editorial Board of Geological Map of Shimane Prefecture. Geological Map of Shimane Prefecture (new version) scale 1:200,000. Naigai Map Co. Ltd., 1997.

[45] Okamoto K, Takahashi Y, Terauchi M. Molluscan assemblage from the Miocene Kawai Formation in Nima-chô, Shimane Prefecture. Professor Hisamichi Matsushita Memorial Volume. Part 2. 1971; 179-185 (in Japanese with English abstract).

[46] Takenouchi S, Tai Y, Kato M. Miocene microbiostratigraphy of Oda City, Shimane Prefecture, west Japan, with specieal reference to the strato-type sections of the Kawai and Kuri formations. Memoirs of the Faculty of Integrated Arts and Sciences, Hiroshima University. Series IV. 1982; **7**: 49-89 (in Japanese with English abstract).

[47] Hayashi H, Hashino S, Nomura R, Tanaka Y. Biostratigraphy of the Miocene Kuri Formation at the type locality in Oda City, Shimane Prefecture, southwestern Honshu, Japan. Journal of the Geological Society of Japan. 2013; **119**: 300-311 (in Japanese with English abstract).

[48] Otofuji Y, Matsuda T. Amount of clockwise rotation of Southwest Japan - fan shape opening of the southwest part of the Japan Sea. Earth and Planetary Science Letters. 1987; **85**: 289-301.

[49] Otofuji Y, Matsuda T. Timing of rotational motion of Southwest Japan inferred from paleomagnetism. Earth and Planetary Science Letters. 1984; **70**: 373-382.

[50] Beck ME Jr. Paleomagnetic record of plate-margin tectonic processes along the western edge of North America. Journal of Geophysical Research. 1980; **85**: 7115-7131.

[51] Sawada Y, Mishiro Y, Imaoka T, Yoshida K, Inada R, Hisai K, Kondo H, Hyodo M. K-Ar ages and paleomagnetism of the Miocene in the Izumo Basin, Shimane Prefecture. Journal of the Geological Society of Japan. 2013; **119**: 267-284 (in Japanese with English abstract).

[52] Jaeger JM, Gulick SPAS, LeVay LJ, the Expedition 341 Scientists. Methods. In: Proceedings of the Integrated Ocean Drilling Program. 2014; **341**:58. doi:10.2204/iodp.proc.341.102.2014

[53] Tada R, Murray RW, Alvarez Zarikian CA, the Expedition 346 Scientists. Methods. In: Proceedings of the Integrated Ocean Drilling Program. 2015; **346**: 71. doi:10.2204/iodp.proc.346.102.2015