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A new secular variation curve for South Kyushu, Japan, and its application to the dating of some lava flows

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Abstract

The remanent magnetization of lava and pyroclastic flows from five dated volcanoes in Kagoshima Prefecture and Nansei Islands were measured. Alternating field and thermal demagnetization experiments reveal that specimens from these lava and pyroclastic flows preserve a stable remanent magnetization. The site mean directions of 55 sampling sites were corrected for the local magnetic declination and inclination values measured using a fluxgate type magnetometer at each locality. A new secular variation curve for South Kyusyu is established and applied for the age determination of some lava flows with unknown ages.

Key words : paleomagnetism, local geomagnetic anomaly, secular variation curve, lava and pyroclastic flow, South Kyusyu

1. Introduction

Studies on the geomagnetic secular variation using baked clays, bricks and potteries from kilns have been carried out by Thellier (1937) and others. In Japan, Kato and Nagata (1953), Watanabe (1958, 1959) and Yukutake (1961) early accumulated archeomagnetic data. Kawai *et al.* (1965) and Hirooka (1971) have measured in detail baked clays mainly in the Kinki district, Japan. Recently, lava flows and pyroclastic sediments in southern Kyushu instead of the baked clays were used for secular variation studies (Ueno *et al.*, 1997a, 2007; Miki 1999; Miki *et al.*, 2002).

Lava flows and pyroclastic flows in Kagoshima and Miyazaki Prefectures including Nansei Islands, called "South Kyushu" afterwards, were measured paleomagnetically. All directional data were corrected for the local magnetic declination and inclination according to measurements obtained with a fluxgate type magnetometer in each sampling site. The remanent directions of Sakurajima volcano have been corrected in similar way (Ueno *et al.*, 2006).

2. Lava and Pyroclastic Flows Used for Paleomagnetic Studies

Eleven active volcanoes are known in South Kyushu (Japan Meteorological Agency, 2005). Among these, Kirishimayama, Sakurajima, Kaimondake, Satsuma-Iojima, Kuchinoerabujima and Suwanosejima volcanoes (Fig. 1) have erupted lava and pyroclastic flows during the past two thousand years (Table 1). Eight lava flows and two pyroclastic flows of known age were selected to produce a secular variation (SV) curve for South Kyushu and seven lava flows of unknown age were selected to determine their age using this SV curve.

The geological outlines of five volcanoes of Kirishimayama, Kaimondake, Satsuma-Iojima, Kuchinoerabujima

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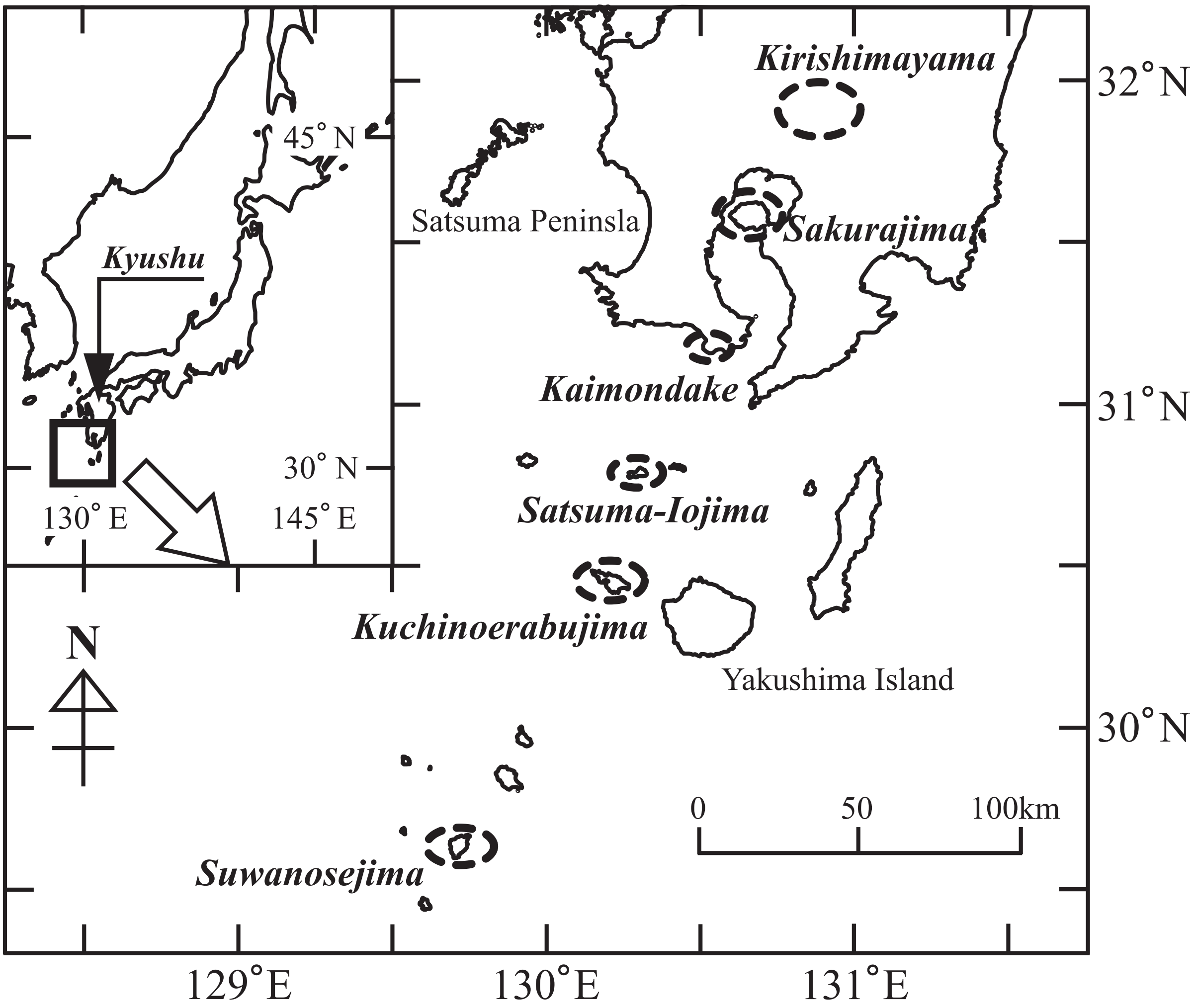

Fig.1 Active volcanoes studied in South Kyushu, Japan.

and Suwanosejima and the description of sampling sites from these volcanoes are as follows.

2.1. Kirishimayama volcano

The composite volcano of Kirishimayama is located at the prefectural border between Kagoshima and Miyazaki, with a N-W elongation of 30 km and a width of 20 km. The field is composed of twenty distinct volcanic structures.

Volcanic activity started 300 ky B.P. and still continues today with fumaroles at Ohachi and Shinmoe-dake volcanoes.

Kyoho pyroclastic flow of Shinmoe-dake volcano (Imura and Kobayashi, 1991) and Takachiho-gawara lava, Ohachi scoria flow, Sano lava and Kirishima-jingu lava of Ohachi volcano (Tsutsui *et al.*, 2006) were sampled for this study.

The Sano lava consists of two-pyroxene andesite, and both Takachiho-gawara and Kirishima-jingu lavas consist of olivine two-pyroxene andesite. Reddish surfaces on the lavas due to oxidation at the cooling stage are recognized. Oriented samples of gray color were collected from the inner flow parts. The Ohachi scoria flow is composed of an oxidized reddish surface part of thickness of five meters and a black interior part, and samples were collected from both parts. The Kyoho pyroclastic flow consists of gray two-pyroxene andesite and samples were obtained from scoria and black lava parts.

Table.1 Table 1. Lava and pyroclastic flows during the past 2000 years in South Kyushu, Japan.

Volcano	Lava or Pyroclastic flow	Age of eruption (year)	This study
Kirishimayama (31.9° N, 130.9° E)			
Io-yama	Io-yama lava	1768A.D. (1)	
Shinmoe-dake	Bunsei pyroclastic flow	1822A.D. (2)	
	Meiwa pyroclastic flow	1771-1772A.D. (2)	
	Kyoho pyroclastic flow	1716-1717A.D. (2)	○
Ohachi	Takachiho-gawara lava	0.7 ky B.P. (3)	○
	Ohachi scoria flow	1235A.D. (3), (4)	○
	Sano lava	0.9-1.1 ky B.P. (3)	○
	Kirishima-jingu lava		○
	Takaharu stage	1235A.D. (3)	
	Katazoe stage	788A.D. (3)	
Sakurajima (31.6° N, 130.6° E)			
	Showa lava	1946A.D. (5)	○
	Taisho lava	1914-1915A.D. (5)	○
	Anei lava	1779A.D. (5)	○
	Bunmei lava	1471-1476A.D. (5)	○
	Nagasaki-bana lava	764A.D. (4), (5), (6)	○
Kaimondake (31.2° N, 130.5° E)			
	Tanosaki lava	885A.D. (7)	○
	Km12b pyroclastic flow	885A.D. (7)	○
	Km12a pyroclastic flow	874A.D. (7)	
	Yokose lava	1.5 ky B.P. (7)	○
	Juccho lava	1.5 ky B.P. (7)	○
Satsuma-Iojima (30.8° N, 130.3° E)			
	YIo3a pyroclastic flow	1.0 ky B.P. (8)	
	Io-dake lava	0.9-2.2 ky B.P. (9)	○
		1.0-2.3 ky B.P. (10)	
		1.5-3.1 ky B.P. (11)	
Kuchinoerabujima (30.4° N, 130.2° E)			
Shin-take	Shin-take lava	0.9-1.0 ky B.P. or 1.2 ky B.P .(12)	○
Furu-take	Nanakama pyroclastic flow	1725-1813A.D. (13)	
	Younger furu-take pyroclastic flow	0.9-1.1 ky B.P. and 3.0-3.2ky B.P. (14)	
	Hiratoko lava	1.1-3.0 ky B.P. (14)	
Suwanosejima (29.6° N, 129.7° E)			
	Meiji lava	1884A.D. (15)	
	Bunka lava	1813-1814A.D. (15)	○

Directions of remanent magnetization of lavas of Sakurajima refer to Ueno *et al.* (2007). References are as follows, (1) Imura and Kobayashi (2001), (2) Imura and Kobayashi (1991), (3) Tsutsui *et al.* (2006), (4) Okuno *et al.* (1998), (5) Kobayashi (1982), (6) Miki (1999), (7) Fujino and Kobayashi (1997), (8) Maeno and Taniguchi (2005), (9) Kawanabe and Saito (2002), (10) Okuno *et al.* (2000), (11) Ono *et al.* (1982), (12) Miki *et al.* (2002), (13) Kobayashi *et al.* (2002), (14) Geshi and Kobayashi (2006), (15) Hirasawa and Matsumoto (1983).

2.2. Kaimondake Volcano

Kaimondake volcano is situated at the south end of Satsuma Peninsula, and has a circular cone shape of 4.5 km basal diameter and 992 m height. Mount Kaimon-dake is a beautiful stratovolcano, and also called Satsuma Fuji. It is a typical double volcano with a central cone at the top (Fujino and Kobayashi, 1997). Its volcanic activity started around 3.7-4.0 ky B.P. (Fujino and Kobayashi, 1997; Kawanabe and Sakaguchi, 2005) and continues today, as shown by an earthquake swarm in 1967 and fumarolic gases in 2000 (Japan Meteorological Agency, 2005).

Oriented samples were collected from Tanosaki lava, Yokose lava, Juccho lava and Km12b pyroclastic flow.

The lava flows are olivin-orthopyroxene bearing clinopyroxene basalts, and samples were taken only from the inner grayish massive portion, and not from the reddish surface portion. The Km12b pyroclastic flow is characterized by black scoria including two-pyroxene andesite blocks, and it also has an oxidized reddish surface. Samples were taken from both the black and reddish portions.

2.3. Satsuma-Iojima Volcano

Satsuma-Iojima volcano is 50 km south of Mount Kaimondake. It forms a volcanic island extending 5.5 km E-W and 4 km N-S. Its volcanic activity started 5.2 ky B.P.

Io-dake lava flow (Ono *et al.*, 1982: Kobayashi, 1989a) is composed of orthopyroxene bearing clinopyroxene rhyolite. Oriented samples were collected from both the reddish oxidized surface and the gray interior portions.

2.4. Kuchinoerabujima Volcano

Kuchinoerabujima Island is a volcanic island 14 km west of Yakushima Island, and has a length of 13 km in W-NW to E-NE direction. The island is composed of nine volcanoes with Furu-take and Shin-take in the central part. Volcanic activity started 580 ky B.P. and still continues at present.

Oriented samples were collected from the Shin-take lava flow of the Shin-take volcano. This lava flow consists of two-pyroxene andesite, and has reddish surfaces due to oxidation during the cooling phase. Samples were taken from the reddish oxidized and/or gray fresh portions.

2.5. Suwanosejima Volcano

The volcanic island of Suwanosejima is located 180 km south of Satsuma Peninsula. Four volcanic bodies are arranged in a N-NE direction over a distance of 9 km.

Oriented samples were collected from the Bunka lava flow, a two-pyroxene andesite (Kobayashi, 1989b).

3. Sampling and Geomagnetic Field Observation

3.1. Sampling Procedure

Six to fourteen cores were collected from each site with a core-drilling machine, or three to eight block samples by hand. A sun compass described in detail by Ueno *et al.* (1997b) was used for orientation. Each core was cut into cylinder specimens of 22 mm in length by 25 mm diameter.

3.2. Geomagnetic Field Observation

On the top and side of a volcanic body a geomagnetic anomaly is usually observed due to the magnetization of the volcanic rock (Yokoyama, 1969). Yukutake *et al.* (1964) have tried to correct the remanent directions of tuff layers with the local geomagnetic anomalies. Watanabe (1959) rejected some data from lava flows assuming that rock samples collected on the mountain side of the volcano may represent not the real ancient field direction because they were affected by local geomagnetic anomalies.

The measurement of the local geomagnetic field was carried out using an equipment consisting of a fluxgate magnetometer, Bartington Model MAG-01H, and a non-magnetic theodolite, Model MG2KP of YOM (Hungary) for the solar position. To obtain the absolute values of horizontal and vertical components, proton magnetometers of Geometrics Model G-856 and Gem System Model GMS-19 were used. Measurements of the geomagnetic field in all sampling sites were done at three or more points within 200 m apart from the outcrop.

4. Measurements of Remanent Magnetization

4.1. Measurering Instruments

Remanent magnetization was measured with a Schonstedt SSM-2A spinner magnetometer. Alternating field demagnetization up to 80 mT was done using a laboratory-made demagnetizer with a three-axis tumbler, and up to 200 mT with an uniaxial-three position coil. A Schonsted TSD-1 thermal demagnetizer with an inlet attachment for Ar gas was employed for thermal demagnetization. Magnetic susceptibility was measured with a Bartington MS-2 magnetic susceptibility meter.

4.2. Paleomagnetic Measurements and Characteristics of Magnetization

Two specimens from each of the 61 sampling sites were alternating field demagnetized in 10 steps up to 80 mT, and some specimens having high coercivity were treated up to 200 mT. One or two specimens from each lava or pyroclastic flow unit were thermally demagnetized in 10 or 12 steps up to 700°C. Magnetic susceptibility after each thermal demagnetization step was measured for monitoring chemical changes of magnetic minerals.

In Fig. 2, typical alternating field and thermal demagnetization curves are shown for four rock units. Alternating field demagnetization reveals that generally small secondary components are completely removed during the first demagnetization steps, and it is possible to get original stable magnetizations. Similarly, a stable component was also found at around the 500ºC step of thermal demagnetization. The stable directions derived from both alternation field and thermal demagnetization procedures are similar. Characteristics of remanent magnetization mentioned above indicate that the stable remanent magnetization must be a thermal remanent magnetization.

About ten specimens from each sampling site were selected. Each specimen was demagnetized in ten alternating field steps, i.e. 5, 10, 20, 25, 30, 40, 50, 60, 70 and 80 mT. Each direction of remanent magnetization was determined by principal component analysis of the alternating field demagnetization data (Kirschvink, 1980). The mean direction of 55 sampling site was calculated (Fisher, 1953) from 4 to 12 specimen data including the data of pilot measurements and is listed in Tables 2, 3 and 4. Six sites among 61 sampling sites were rejected, because their site mean directions were quite different to each other and were considered as the result of block movement after cooling.

The geomagnetic local anomaly for each sampling site was obtained by the difference of the declination and inclination, between observed value and calculated value of the geomagnetic chart (1990) on Chronological Scientific Tables (National Astronomical Observatory, 1998).

The geomagnetic field observations of each sampling site were done at three or more points within 200 m apart from the outcrop. The correction is effective, because the local anomalies are produced by magnetization of the volcano body which had occupied there when lava and pyroclastic flows erupted. The correction value is random for different lava and pyroclastic flows, and reaches 4.4 degrees at its maximums.

In order to estimate the effect of the local anomaly correction lava units or pyroclastic flow units, which are separate populations and have the same age, are favorable. Only the Tanosaki lava (western part) and the Km12b pyroclastic flow (south eastern part) of Kaimondake volcano have the same age 885A.D. (Fujino and Kobayashi, 1997) among the data of the lava or pyroclastic flow unit level in this work. The mean direction of remanent magnetization calculated from corrected and non-corrected values in Tables 2, 3 and 4 are as follows; Tanosaki lava non-corrected (348.4, 50.9), Tanosaki lava corrected (346.2, 48.7), Km12b pyroclastic flow non-corrected (341.8, 44.2), Km12b pyroclastic flow corrected (344.5, 43.0). The difference of both mean directions decreases from 8.0 degrees to 5.8 degrees by the anomaly correction. To compare whether the mean directions of two populations, Tanosaki lava and Km12b pyroclastic flow, are similar, F-test (McFadden and Lowes, 1981) was carried out. The F-values in the non-corrected and corrected cases are 28 and 13, respectively. The F-table with degrees of freedom of $\Phi_1 = 2$ and $\Phi_2 = 2$ (N-2) where N = 8 at the 1% level indicates 9.3. Although the F-values of both case are over

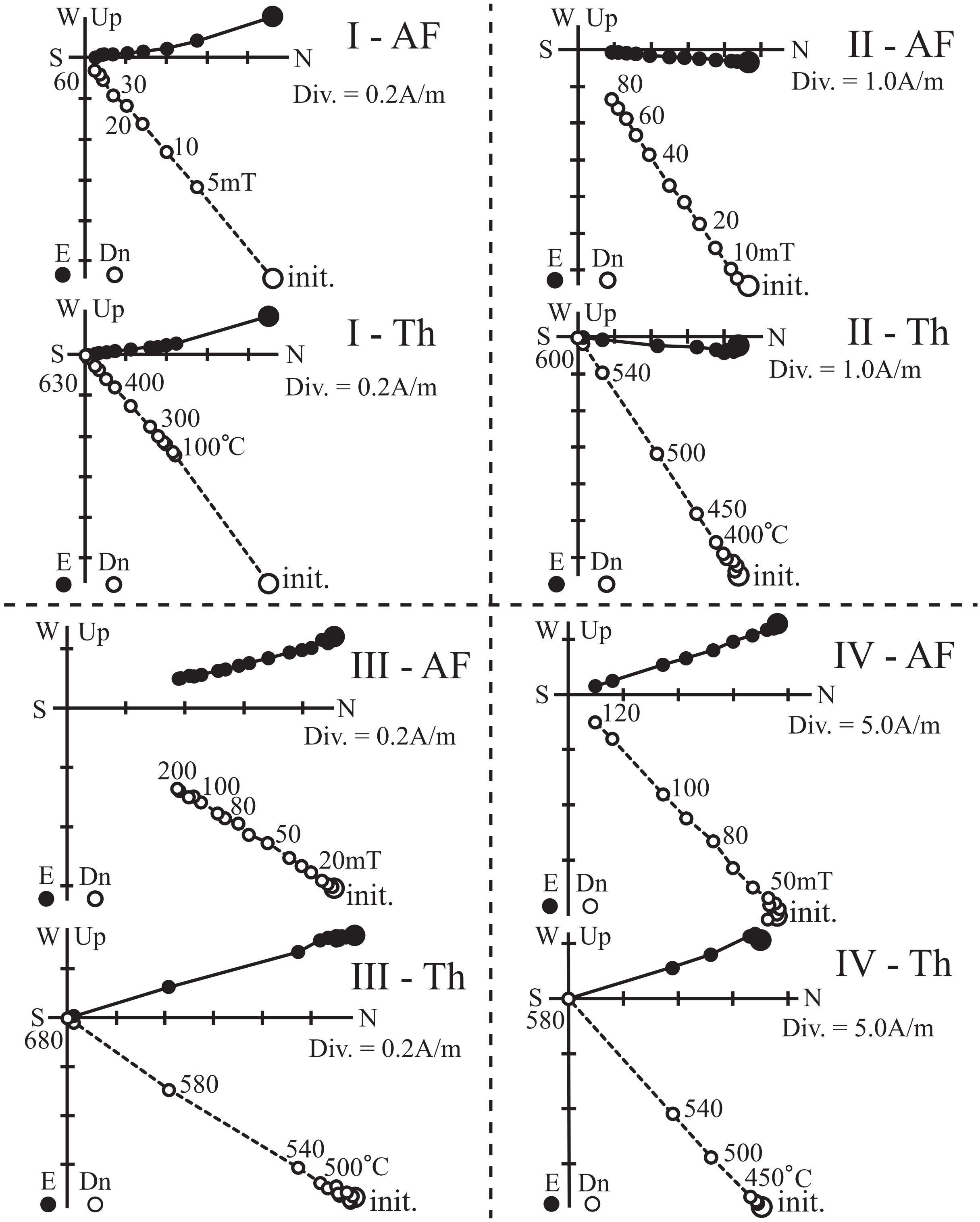

Fig.2 Orthogonal projection (Zijderveld, 1967) of alternating field (AF) and thermal (Th) demagnetization.
I : Shin-take lava (9016, gray), II : Kirishima-jingu lava (3076, gray), III : Io-dake lava (1040, reddish), IV : Km12b pyroclastic flow (8104, reddish).

Table 2. The site mean direction of remanent magnetization of lava and pyroclastic flows of Kirisimayama (Ohachi) volcano.

Volcano Lava or Pyroclastic flow	Site Lat. (°) / Lon. (°)	N	D (°) Dc (°)	I (°) Ic (°)	a95 (°)	k	R	ΔD (°)	ΔI (°)
Kirishimayama Ohachi									
Takachiho-gawara lava	6028 - 6039	5	000.1	48.8	3.0	635	4.994	0.4	0.2
	31.874 / 130.900		359.7	48.6					
	6049 - 6057	4	359.2	50.3	3.7	611	3.995	-0.6	-0.3
	31.881 / 130.892		359.8	50.6					
	6058 - 6062	5	001.4	53.6	2.1	1368	4.997	0.4	0.2
	31.874 / 130.900		001.0	53.4					
	6063 - 6067	5	003.3	51.6	2.2	1168	4.997	-0.6	-0.3
	31.881 / 130.892		003.9	51.9					
Ohachi scoria flow	5018 - 5030	12	003.4	52.7	1.5	792	11.99	-0.7	-0.4
	31.882 / 130.893		004.1	53.1					
	5031 - 5044	12	001.0	51.7	1.7	655	11.98	0.0	0.3
	31.884 / 130.894		001.0	51.4					
	5045 - 5058	14	005.3	53.1	1.6	633	13.98	-0.5	0.4
	31.887 / 130.897		005.8	52.7					
	5059 - 5071	13	001.6	51.1	1.9	532	12.98	-0.5	0.4
	31.888 / 130.898		002.1	50.7					
Sano lava	4024 - 4031	11	357.8	42.3	1.9	608	10.98	-1.0	-0.3
	31.904 / 130.954		358.8	42.6					
	4032 - 4041	9	358.6	46.6	1.4	1330	8.994	-0.7	0.3
	31.904 / 130.954		359.3	46.3					
	4042 - 4054	12	357.7	44.5	1.6	758	11.99	0.6	2.3
	31.903 / 130.951		357.1	42.2					
	4055 - 4065	11	001.2	45.0	1.6	864	10.99	1.4	-1.1
	31.909 / 130.929		359.8	46.1					
Kirishima-jingu lava	3031 - 3039	12	351.7	43.3	1.8	585	11.98	-0.2	-1.2
	31.871 / 130.896		351.9	44.5					
	3040 - 3049	10	345.6	47.3	1.7	821	9.989	-0.2	-1.2
	31.870 / 130.894		345.8	48.5					
	3050 - 3059	10	351.0	37.1	1.2	1680	9.994	-0.9	-1.7
	31.853 / 130.876		351.9	38.8					
	3060 - 3067	11	352.6	47.2	1.7	706	10.99	1.3	1.1
	31.870 / 130.878		351.3	46.1					
	3076 - 3083	12	002.5	54.0	0.9	2240	11.99	-0.7	-0.4
	31.882 / 130.893		003.2	54.4					
	3084 - 3094	11	006.0	49.5	1.7	709	10.99	-0.6	-0.3
	31.881 / 130.892		006.6	49.8					
	3095 - 3102	11	354.9	42.9	2.1	466	10.98	1.3	1.1
	31.870 / 130.877		353.6	41.8					
	3103 - 3110	10	004.3	46.3	1.8	766	9.988	0.2	-0.6
	31.849 / 130.866		004.1	46.9					
	3111 - 3118	11	006.3	44.4	1.4	1020	10.99	0.2	-0.6
	31.850 / 130.866		006.1	45.0					

Lat. and Lon. : latitude and longitude, N : number of specimens, D and I : mean direction of declination and inclination, Dc and Ic : corrected mean direction (D-ΔD and I-ΔI), ΔD and ΔI : geomagnetic anomaly direction, a95 and k : half angle of the cone of confidence at p=0.95 and best estimation of precision (Fisher, 1953), R : the resultant of vector sum.

than 9.3, the F-value of 13 in the corrected case is clearly smaller than the F-value of 28 in the non-corrected case. It means that the F-value in the corrected case is close to the significant level.

Then, the local anomaly corrections were adopted towards whole sites in this work. The mean direction of lava and pyroclastic flow units illustrated as Table 5 is calculated from the site mean direction (Dc and Ic in Tables 2, 3 and 4).

Here, mean direction of the Kirishima-jingu lava is not calculated, because the Kirishima-jingu lava consists of two eruption stages (788A.D. and 1235A.D.) lava flows with unknown distribution (Tsutsui *et al.*, 2006) and it is impossible to distinguish the stage in the field.

Table 3. The site mean direction of remanent magnetization of lava and pyroclastic flows of Kirisimayama (Shinmoe-dake) and Kaimondake volcanoes.

Volcano Lava or Pyroclastic flow	Site Lat. (°) / Lon. (°)	N	D (°) Dc (°)	I (°) Ic (°)	a95 (°)	k	R	ΔD (°)	ΔI (°)
Kirishimayama Shinmoe-dake									
Kyoho pyroclastic flow	7001 - 7006 31.915 / 130.882	8	000.6 359.9	36.5 33.2	2.9	357	7.980	0.7	3.3
	7007 - 7012 31.914 / 130.881	8	001.3 000.6	39.4 36.1	3.1	315	7.978	0.7	3.3
	7013 - 7018 31.911 / 130.894	8	001.0 002.3	37.5 35.8	1.8	911	7.992	-1.3	1.7
	7019 - 7024 31.911 / 130.894	8	002.1 003.4	34.8 33.1	1.1	2461	7.997	-1.3	1.7
Kaimondake									
Tanosaki lava	8001 - 8004 31.178 / 130.506	4	346.3 344.1	50.3 48.1	1.8	2619	3.999	2.2	2.2
	8005 - 8009 31.178 / 130.506	5	348.6 346.4	49.8 47.6	1.1	4953	4.999	2.2	2.2
	8092 - 8097 31.178 / 130.508	6	349.0 346.8	51.0 48.8	2.0	1185	5.996	2.2	2.2
	8098 - 8103 31.178 / 130.508	6	349.8 347.6	52.3 50.1	1.4	2169	5.998	2.2	2.2
Km12b pyroclastic flow	8074 - 8077 31.173 / 130.544	4	340.9 343.6	47.6 46.4	5.2	310	3.990	-2.7	1.2
	8078 - 8081 31.173 / 130.544	4	343.0 345.7	43.3 42.1	3.8	577	3.995	-2.7	1.2
	8104 - 8107 31.172 / 130.543	4	341.7 344.4	41.5 40.3	3.4	742	3.996	-2.7	1.2
	8108 - 8112 31.172 / 130.543	4	341.6 344.3	44.5 43.3	6.8	185	3.984	-2.7	1.2
Yokose lava	8019 - 8029 31.165 / 130.522	9	350.7 349.6	49.7 49.5	1.4	1296	8.994	1.1	0.2
	8030 - 8040 31.166 / 130.519	11	350.8 349.4	45.8 45.6	1.9	558	10.98	1.4	0.2
	8063 - 8073 31.173 / 130.511	11	347.0 346.3	41.7 41.7	1.7	721	10.99	0.7	0.0
Juccho lava	8010 - 8018 31.180 / 130.509	9	351.8 351.3	53.2 51.1	1.6	1056	8.994	0.5	2.1
	8041 - 8052 31.195 / 130.530	12	349.7 348.9	56.3 56.6	1.8	764	11.99	0.8	-0.3
	8053 - 8062 31.194 / 130.537	10	351.8 351.4	57.1 57.3	1.0	2194	9.996	0.4	-0.2
	8082 - 8091 31.167 / 130.542	10	344.1 348.5	45.5 45.9	0.7	4755	9.998	-4.4	-0.4

Lat., Lon., N, D, I, Dc, Ic, ΔD, ΔI, a95, k and R : same as Table 2.

5. Secular Variation Curve for South Kyushu

We determined a new secular variation (SV) curve for South Kyushu using the remanent directions of this study and previous reports which were corrected with the local geomagnetic anomaly values. For this, direction data were recalculated for a locality at 30.8°N, 130.3°E in South Kyushu by assuming a geocentric dipole field. Fig. 3 shows the new SV curve for South Kyushu. The SV curve is an approximation curve drawn by a polynomial function. The polynomial approximate method used here is based on a regression analysis, which is included in Excel 2003 of Microsoft Corporation, and the calculation is executed within sixth order. The coefficients of correlation in declination and inclination curves are around 0.94 and 0.91, respectively. It is proper that the curve may be updated by addition of future new data. The larger the direction change of the geomagnetic field is, the smaller an estimation error becomes. Judging from the steepness of lines, the estimation error is longer than 20 years per 1 degree of declination and inclination.

Table 4. The site mean direction of remanent magnetization of lava flows of Satsuma-Iojima, Kuchinoerabujima and Suwanosejima volcanoes.

Volcano Lava flow	Site Lat. (°) / Lon. (°)	N	D (°) Dc (°)	I (°) Ic (°)	a95 (°)	k	R	ΔD (°)	ΔI (°)
Satsuma-Iojima									
Io-dake lava	1001 - 1010 30.787 / 130.296	8	352.9 352.6	38.0 37.3	1.8	1006	7.993	0.3	0.7
	1021 - 1031 30.788 / 130.296	11	348.5 348.2	32.8 32.1	2.7	289	10.97	0.3	0.7
	1032 - 1040 30.782 / 130.298	7	344.4 344.2	34.0 32.8	1.8	1174	6.995	0.2	1.2
Kuchinoerabujima Shin-take									
Shin-take lava	9001 - 9006 30.455 / 130.194	12	358.0 358.6	49.2 49.7	1.3	1150	11.99	-0.6	-0.5
	9007 - 9013 30.455 / 130.194	13	000.0 000.6	52.2 52.7	1.4	848	12.99	-0.6	-0.5
	9014 - 9019 30.455 / 130.194	12	355.3 355.9	49.0 49.5	1.4	931	11.99	-0.6	-0.5
	9020 - 9025 30.455 / 130.194	10	357.2 357.8	47.8 48.3	1.3	1394	9.999	-0.6	-0.5
	9037 - 9044 30.455 / 130.194	10	357.3 357.9	48.3 48.8	2.0	574	9.980	-0.6	-0.5
	9045 - 9048 30.455 / 130.194	10	000.3 000.9	48.1 48.6	1.5	1067	9.999	-0.6	-0.5
	9049 - 9055 30.441 / 130.202	10	351.6 351.6	46.0 45.1	0.7	4753	9.999	0.0	0.9
	9056 - 9064 30.439 / 130.203	11	358.9 358.9	49.4 48.5	0.7	4520	10.99	0.0	0.9
Suwanosejima									
Bunka lava	2001 - 2010 29.629 / 129.688	8	353.9 353.7	38.2 35.6	2.9	362	7.981	0.2	2.6
	2011 - 2019 29.630 / 129.688	9	353.5 353.3	37.3 34.7	1.6	1020	8.992	0.2	2.6
	2026 - 2034 29.641 / 129.684	9	354.8 355.0	37.2 35.0	1.4	1384	8.994	-0.2	2.2
	2035 - 2043 29.642 / 129.684	10	356.1 356.3	36.6 34.4	1.9	668	9.987	-0.2	2.2

Lat., Lon., N, D, I, Dc, Ic, ΔD, ΔI, a95, k and R : same as Table 2.

It has been suggested that SV curves differ from district to district (Hirooka, 1981; Hirooka and Fujisawa, 2002). As shown in Fig.3, the SV curve for South Kyushu is similar to that for the Kinki district (Hirooka, 1971) except for short time periods around 1500A.D.

The SV curve for South Kyushu (Fig. 3) is considered to be very reliable, because it is based on the stable thermal remanent magnetization mainly from lava flows at South Kyushu and it is corrected for the local geomagnetic anomaly values.

6. Paleomagnetic Dating on Lava Flows

Seven lava flows with uncertain ages are indicated in Table 1, and their dating was attempted using the new secular variation curve for South Kyushu (Fig. 3). This new SV curve is limited to ages younger than 700 A.D., and therefore only the dating of the following three lava flows may be attempted.

Sano lava

The Sano lava is younger than the Kirishima-jingu lava of Katazoe stage (788A.D.), and older than the Kirishima-jingu lava of Takaharu stage and the Ohachi scoria flow (1235A.D.) (Tsutsui *et al.*, 2006). No correspondence of both their declination and inclination with the SV curves are found (Fig. 4(a)). It is impossible

Table 5. The mean direction of remanent magnetization of lava and pyroclastic flow units.

Volcano	Lava or Pyroclastic flow	N	D (°) Dr (°)	I (°) Ir (°)	a95 (°)	k	R
Kirishima-yama							
Shinmoe-dake	Kyoho pyroclastic flow	4	001.6 001.5	34.6 32.9	2.4	1503	3.998
Ohachi	Takachiho-gawara lava	4	001.1 001.1	51.1 49.9	2.7	1162	3.997
	Ohachi scoria flow	4	003.2 003.2	52.0 50.8	2.0	2213	3.999
	Sano lava	4	358.7 358.6	44.3 42.9	2.7	1181	3.997
Kaimon-dake	Tanosaki lava	4	346.2 346.2	48.7 48.3	1.7	3040	3.999
	Km12b pyroclastic flow	4	344.5 344.5	43.0 42.6	3.0	940	3.997
	Yokose lava	3	348.4 348.4	45.6 45.2	6.3	388	2.995
	Juccho lava	4	350.0 350.1	52.7 52.3	6.2	225	3.987
Satsuma Io-jima	Io-dake lava	3	348.3 348.3	34.1 34.1	6.8	330	2.994
Kuchinoerabu-jima							
Shin-take	Shin-take lava	8	357.7 357.7	48.9 49.3	2.0	794	7.991
Suwanose-jima	Bunka lava	4	354.6 354.7	34.9 36.5	1.4	4350	3.999

N : number of sites, Dr and Ir : recalculated direction for the center point of 30.8°N, 130.3°E in South Kyushu. D, I, a95, k and R : same as Table 2.

to determine the age with this method.

Takachiho-gawara lava

The Takachiho-gawara lava is younger than both Kirishima-jingu lava of Takaharu stage and Ohachi scoria flow (1235A.D.) (Tsutsui *et al.*, 2006). As shown in Fig. 4(b), an age the 13th Century A.D. latter half is suggested.

Shin-take lava

The resolution by the present method is only one, the 12th Century A.D. (Fig. 4(c)). Miki *et al.* (2002) reported an estimated age for this lava of the later half of the 8th Century or the 11th Century A.D.

7. Summary

Seventeen lava and pyroclastic flows of Kirishimayama, Kaimondake, Satsuma-Iojima, Kuchinoerabujima and Suwanosejima volcanoes together with Sakurajima volcano in South Kyushu were studied paleomagnetically.

The results are summarized below.

(1) Each lava and pyroclastic flows preserve stable thermal magnetizations.

(2) Alternating field demagnetization and thermal demagnetization experiments reveal that the magnetization is the thermal remanent magnetization, and it is easy to remove the secondary magnetization and to obtain the original stable thermal remanent magnetization by the alternating field demagnetization.

(3) Site mean directions were corrected by the geomagnetic local anomaly values measured at each sampling site.

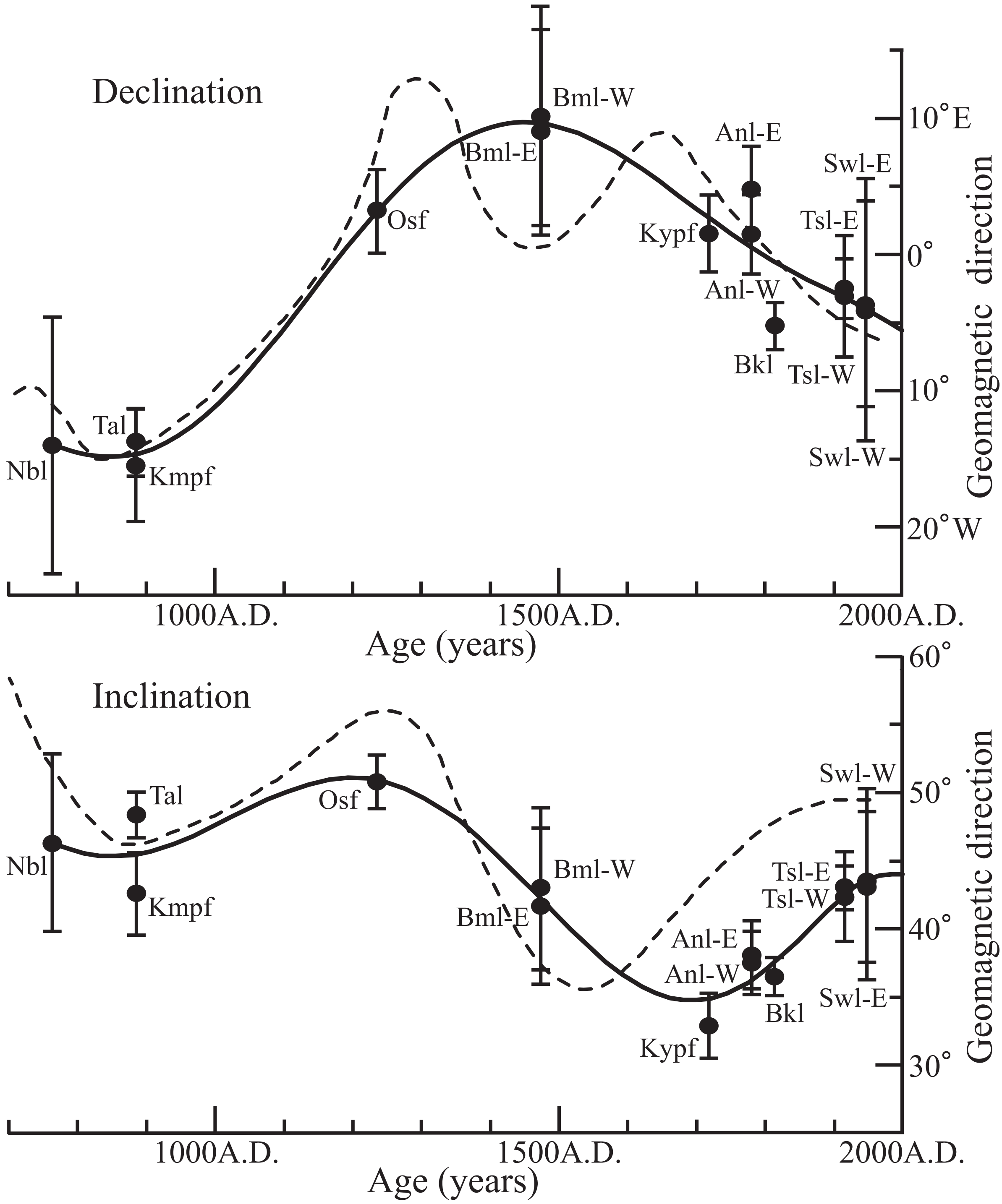

Fig. 3. Secular variation curve for South Kyushu (solid line) with Kinki district curve (broken line) by Hirooka (1971).

Solid circle and vertical line : recalculated archeomagnetic direction and confidence limits (95%) for the center point in South Kyushu. Tal and Kmpf : Tanosaki lava and Km12b pyroclastic flow (885A.D.), Osf : Ohachi scoria flow (1235A.D.), Kypf : Kyoho pyroclastic flow (1716-1717A.D.), Bkl : Bunka lava (1813-1814A.D.), respectively (this study). Nbl : Nagasaki-bana lava (764A.D.), Bml-E and W : Bunmei lava east and west (1471-1476A.D.), Anl-E and W : Anei lava east and west (1779A.D.), Tsl-E and W : Taisho lava east and west (1914-1915A.D.), Swl-E and W : Showa lava east and west (1946A.D.), respectively (Ueno *et al.*, 2006).

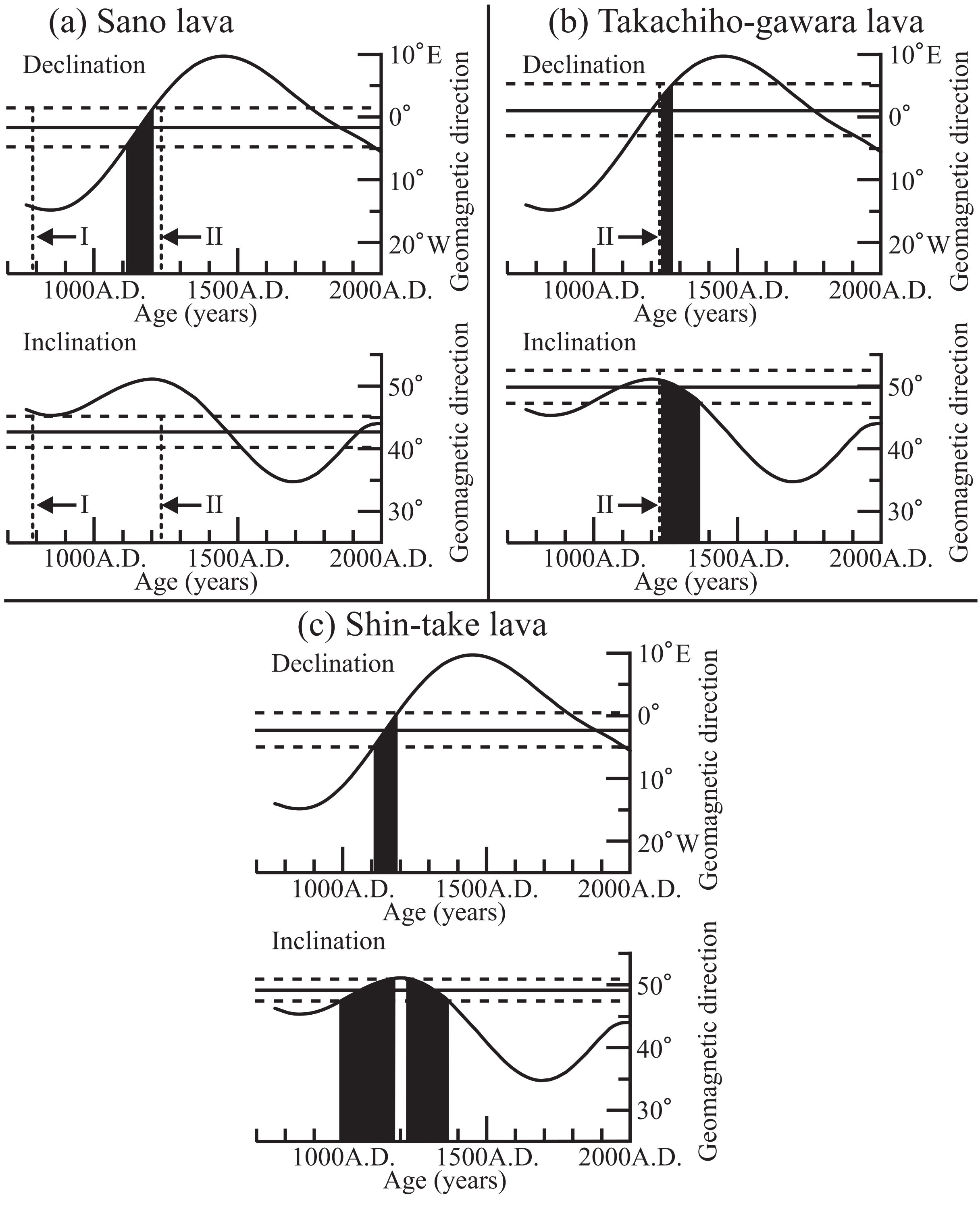

Fig. 4. Direction of remanent magnetization of Sano lava, Takachiho-gawara lava and Shin-take lava, plotted on secular variation curve for South Kyushu.

Horizontal solid and broken lines are recalculated archeomagnetic direction and confidence limits (95%) for the center point in South Kyushu. I : Kirishima-jingu lava of Katazoe stage (788A.D.), II : Kirishima-jingu lava of Takaharu stage (1235A.D.) and Ohachi scoria flow (1235A.D.). Details in the text.

(4) A new secular variation curve for South Kyushu is established using the anomaly-corrected data of lava and pyroclastic flows, covering the age range between 700 and 2000 A.D.
(5) The lava flows of previously uncertain age could be dated by comparing their paleomagnetic record with the secular variation curve.

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