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Paleomagnetism of Unzen volcano: A volcanic record (Senbongi excursion) of the Iceland Basin event and the Brunhes VGP distribution for Japan

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A paleomagnetic study was carried out on volcanic rocks from Unzen volcano: samples were collected from a total of 69 sites with 19 sites in pyroclastic flows and 50 sites in lava flows. Ages for the flows were determined either by K-Ar methods or detailed field surveys, and indicate that all of the flows were deposited during the Brunhes chron. After demagnetization 10 pyroclastic and 48 lava flows had stable site-mean directions. One lava flow in the Senbongi area with a K-Ar age of 197±17 ka had an intermediate virtual geomagnetic pole (VGP) at 8.3°N, 21.6°E. The age and VGP position apparently correlate with the Iceland Basin event, suggesting that it is a record of the event on volcanic rocks. Our study added 53 Brunhes-aged VGPs to the overall collection for Japan, increasing it by 40% to a total of 175 VGPs. After excluding all site-mean directions having $\alpha_{95} > 10°$ and VGP latitude $< 50°$, the remaining 148 VGPs have a mean pole at 89.7°N, 40.9°E ($A_{95} = 2.2°$) showing no significant deviation from the geographic pole. The angular standard deviation (ASD) was calculated as $15.2° \pm 1.2°$ ($N = 148$), which is compatible with paleosecular variation models from the literature. However, the data set was found to deviate from a Fisher distribution. The actual meaning of the ASD value after removing the intermediate VGPs needs to be reconsidered.

Key words: Geomagnetic excursion, Iceland basin event, PSVL, Unzen volcano.

1. Introduction

Unzen volcano, which is situated on the western side of Kyushu Island, Japan, was active during the period from 1991 to 1995 (Nakada *et al.*, 1999; Hoshizumi *et al.*, 1999). The eruptions killed 44 people and the pyroclastic and debris flows destroyed more than 2,000 homes. In order to better understand the hazards associated with the volcano, the Japanese government undertook a number of geologic and geophysical studies. The projects included the Unzen Scientific Drilling Project (USDP) and its auxiliary field studies related to flows in the drill core. A comprehensive paleomagnetic investigation of the Unzen volcano was carried out as a part of the field studies. The objectives of this investigation were two fold: 1) To apply paleomagnetism to volcanological problems, such as assessing the settling temperature of pyroclastic flows and correlating individual lava flows, and 2) to study the record of geomagnetic activities, namely, secular variation and short geomagnetic episodes, within the Brunhes chron. Results related to the first objective have already been reported (Tanaka *et al.*, 2004), and this paper concerns the recorded behavior of the geomagnetic field.

Lava flows have long been studied to unravel the record of paleosecular variation (PSVL) of the geomagnetic field. In a PSVL study each paleomagnetic direction for a lava flow is thought to represent a "snap shot" of the local geomagnetic direction at a point in time when the lava flow cooled, and the statistical parameters of the site-mean directions and/or virtual geomagnetic poles (VGPs) are used to characterize the geomagnetic secular variation. It is essential to determine the shape of the distribution, and this requires much more data than needed to determine the statistical parameters assuming a given distribution. Thus, the accumulation of PSVL data is important for improving our understanding of the geomagnetic field.

As subjects of a PSVL study, Unzen volcanic rocks have two distinct advantages: (1) Detailed geological studies of the volcano have already been made, and (2) reliable ages are available for almost all of the geological units on the volcano, made primarily by the Geological Survey of Japan (GSJ) which is a leading institute of the USDP. Although resolution of the dates is well below the typical periods of geomagnetic secular variation, they are very useful in evaluating the paleomagnetic results.

Another important purpose of the paleomagnetic studies of Brunhes volcanic rocks is finding a geomagnetic excursion, which is a major swing of the geomagnetic field from the axial-dipole field direction. Although existence of geomagnetic excursions used to be a subject of controversy (e.g. Roberts and Piper, 1989), they are now commonly accepted due to improvements in magnetic measurements, dating and correlation of excursion reports in marine sediment cores (e.g. Channell, 1999), and several reliable reports from volcanic rocks (e.g. Shibuya *et al.*, 1992; Tanaka and Kobayashi, 2003). Volcanic records of geomagnetic excursions are important, since they serve as tie points between sediment stratigraphy and radiometric ages, and as calibration points for relative geomagnetic paleointensity logs measured from sediment cores to absolute ones from volcanic rocks. Fortunately, we have found a reliable record of a geomagnetic excursion in a lava flow from Unzen volcano.

2. Geology and Paleomagnetic Measurements

Unzen Volcano has been active for approximately half a million years, and during this time has erupted mostly dacitic lava and pyroclastic flows. It is situated in the Beppu-Shimabara graben that cuts Kyushu Island from east to west; the graben has also given rise to a number of other volcanoes. Tectonic subsidence of the normal-faulted graben is about 2 mm/yr, and volcanic materials have filled in the rift zone. Unzen volcanic rocks are divided into younger and older units based on topography and stratigraphy, and this classification has been verified in most areas by K-Ar ages determined for the USDP. The rock units of "Younger" Unzen were found to range between 150 ka and 0 ka while those of "Older" Unzen range between 500 ka and 150 ka (Hoshizumi *et al.*, 2003). Without ages, it is difficult to distinguish petrographically or geochemically between the older and younger Unzen rocks. Pre-Unzen andesitic and basaltic rocks that underlie Unzen Volcano are between 4.3 and 0.5 million years old.

Paleomagnetic samples were collected from 46 sites in lava flows and 19 sites in pyroclastic flows within the Unzen dacite, and from 4 lava flows in the pre-Unzen andesites and basalts that are from 0.8 to 0.5 Ma in age. Figure 1 shows the distribution of site locations, and these and the age data are tabulated in Table 1. Many paleomagnetic sites are in the same outcrops that were sampled for geochronology by the USDP, or are in flows that are well correlated with dated flows. Paleomagnetic samples were collected primarily using a portable gasoline-powered drill and diamond-tipped drill bits (core diameter of 25 mm and length usually >100 mm), and were oriented using a magnetic compass. A sun compass was also used for orientation whenever possible. The magnetic and sun orientations were compared by Tanaka *et al.* (2004) and were not found to be significantly different for the dacitic rocks of Unzen Volcano. At a few sites in the pyroclastic flows hand samples were collected because the cobble-sized blocks were too difficult to drill. A block orientation tool consisting of a magnetic compass attached to a tripod, commonly used by Japanese paleomagnetists, was used for all hand samples with measurement errors nearly as good as those for the field drilled cores. Usually more than 7 independently oriented samples were taken from each site. Hand samples were drilled with a press in the laboratory to yield cylindrical cores with the same dimensions as those drilled in the field. All cores were then cut into specimens 25 mm in length.

Laboratory measurements were mostly carried out at Kumamoto University. The instruments used in this study were a Natsuhara-Giken SSM-85 spinner magnetometer, a Natsuharra-Giken DEM-8601 tumbling demagnetizer, and a Schonstedt TSD-1 thermal demagnetizer that are all situated in a geomagnetic field-free room. Some measurements were also made using similar Natsuhara-Giken instruments at Kochi University. Before any demagnetization procedures were undertaken, the natural remanent magnetization (NRM) of each specimen was measured. For sites in the lava flows an appropriate pilot specimen was then selected and was progressively demagnetized using alternating fields (a.f.) at 14 steps up to 100 mT. If the majority of the remanence was not removed, a sister specimen was subjected to thermal demagnetization to 680°C or until the NRM was completely removed. If the characteristic component (ChRM) was clearly defined in the orthogonal a.f. demagnetization plot, then specimens from the site's remaining samples were demagnetized at a single 'blanket' step to define the ChRM. Otherwise, the other samples were also progressively a.f. demagnetized. All samples from the sites in pyroclastic flows, however, were submitted to progressive thermal demagnetization to determine the ChRM direction and the settling temperature of the flow, i.e. whether or not the deposit was the result of a hot pyroclastic or cold debris flow.

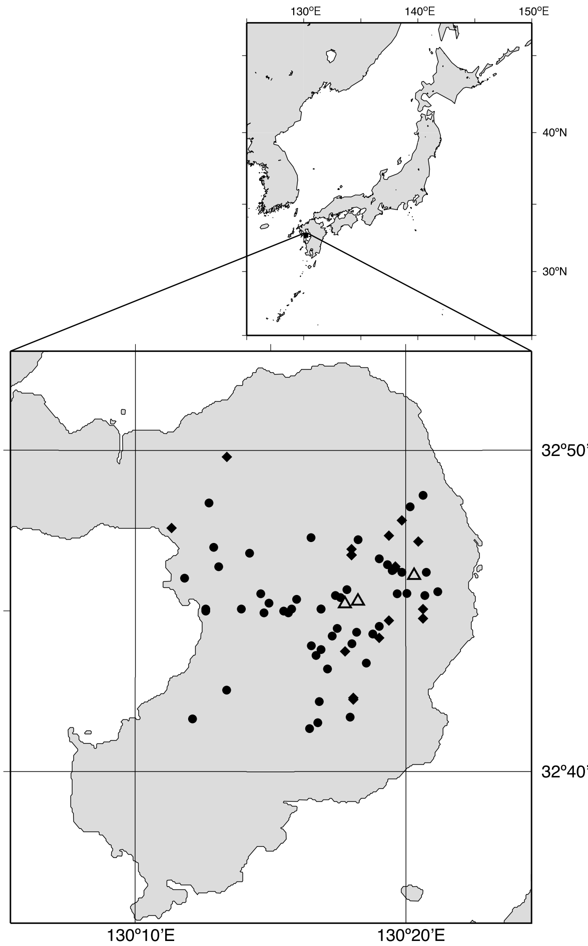


Fig. 1. Map showing the sampling sites. Circles and diamonds represent the lava and pyroclastic sites, respectively. Triangles are Fugendake, Heisei-shinzan and Mayuyama mountains, from left to right.

Table 1. Sampling sites. Lat. and Long. indicate latitude and longitude, respectively. The method of the numerical age is shown in parenthesis; K: K-Ar, C: ^{14}C, F: fission track, others are estimated geologically. The last column indicates the reference of the age. D93: Danhara *et al*. (1993), H99: Hoshizumi *et al*. (1999), H06: http://staff.aist.go.jp/h.hoshizumi/unzen/, M: Matsumoto *et al*. (in prep.), N88: Nakada *et al*. (1988), W93: Watanabe *et al*. (1993).

Site No.	Flow Unit	Site Lat. (°)	Site Long. (°)	Age (ka)	Ref.
Pyroclasitc flow sites					
UZ01	90-95 pcf.	32.746	130.344	0	
UZ02	90-95 pcf.	32.745	130.323	0	
UZ03	Kureisibaru pcf.	32.789	130.323	40±4 (K)	M
UZ04	Yuegawa pcf	32.782	130.300	13.85±0.18 (C)	H06
UZ10	Newer Unzen pcf	32.779	130.300	25.0±1.9 (K)	M
UZ11	Newer Unzen pcf	32.779	130.300	25.0±1.9 (K)	M
UZ12	Newer Unzen pcf	32.779	130.300	25.0±1.9 (K)	M
UZ14	Mutsugi pcf	32.786	130.341	4.22±0.11 (C)	H99
UZ15	Kitakamikoba pcf	32.751	130.344	ca. 5	
UZ17	Yugawachi pcf (lowest part)	32.704	130.301	<80	H99
UZ18	Yugawachi pcf (middle part)	32.705	130.301	<80	H99
UZ22	Older Unzen pcf	32.772	130.327	ca. 300	
UZ23	Older Unzen pcf	32.772	130.326	ca. 300	
UZ24	Older Unzen pcf	32.773	130.327	ca. 300	
UZ25	Older Unzen pcf	32.797	130.331	ca. 300	
UZ30	Nodake pcf	32.729	130.296	73±4 (K)	H99
UZ33	Furue pcf	32.736	130.317	22±5 (K)	M
UZ39	Older Unzen pcf	32.793	130.189	ca. 300	
UZ43	Older Unzen pcf	32.830	130.223	309±8 (K)	M
Lava sites					
UZ05	Shichimenyama lava	32.770	130.346	5.1±1.4 (F)	D93
UZ06	Tenguyama lava	32.758	130.345	ca. 5	
UZ07	Kazaana lava	32.761	130.297	ca. 6	
UZ08	Fugen top lava	32.757	130.293	ca. 6	
UZ09	Tarukidaichi N.	32.770	130.331	197±17 (K)	H99
UZ13	Newer Unzen lava	32.787	130.304	100±60 (K)	M
UZ16	Older Unzen lava	32.810	130.344	308±10 (K)	M
UZ19	Tonosaka andesite	32.689	130.274	500±200 (K)	N88
UZ20	Older Unzen lava	32.695	130.299	ca. 300	
UZ21	Lava from Mayuyama	32.760	130.353	ca. 5	
UZ26	Older Unzen lava	32.732	130.275	240±10 (K)	W93
UZ27	Older Unzen lava	32.720	130.285	432±14 (K)	M
UZ28	Tonosaka andesite	32.727	130.278	500±200 (K)	N88
UZ29	Older Unzen lava	32.730	130.281	198±22 (K)	M
UZ31	Nodake lava	32.739	130.303	73±4 (K)	H99
UZ32	Fukkoshi lava	32.733	130.300	109±4 (K)	H99
UZ34	Older Unzen lava	32.804	130.336	230±20 (K)	M
UZ35	Torikabutoyama lava	32.788	130.275	210±10 (K)	H99
UZ36	Older Unzen lava	32.751	130.210	ca. 300	
UZ37	Older Unzen lava	32.750	130.210	ca. 300	
UZ38	Older Unzen lava	32.767	130.197	260±20 (K)	W93
UZ40	Older Unzen lava	32.749	130.246	ca. 300	
UZ41	Older Unzen lava	32.751	130.232	ca. 300	
UZ42	Older Unzen lava	32.806	130.212	384±40 (K)	M
UZ44	Nodake lava	32.737	130.288	80±20 (K)	W93
UZ45	Nodake lava	32.741	130.291	73±4 (K)	H99
UZ46	Myokendake lava	32.758	130.290	25±10 (K)	H99
UZ47	Fukkoshi lava	32.751	130.281	112±26 (K)	H99
UZ48	Fukkoshi lava	32.751	130.281	112±26 (K)	H99
UZ49	Older Unzen lava	32.750	130.258	ca. 300	

Table 1 (continued).

Site No.	Flow Unit	Site Lat. (°)	Site Long. (°)	Age (ka)	Ref.
Lava sites (continued)					
UZ50	Older Unzen lava	32.749	130.261	238±8 (K)	M
UZ51	Older Unzen lava	32.751	130.263	180±6 (K)	M
UZ52	Older Unzen lava	32.771	130.325	185±7 (K)	M
UZ53	Tarukidaichi NW	32.774	130.322	187±53 (K)	H99
UZ54	Older Unzen lava	32.759	130.328	440±240 (K)	M
UZ55	Fukkoshi lava	32.742	130.317	109±4 (K)	H99
UZ56	Fukkoshi lava	32.738	130.313	115±4 (K)	M
UZ57	Older Unzen lava	32.723	130.309	177±10 (K)	M
UZ58	Taruki-Higashi lava	32.759	130.334	25±12 (K)	H99
UZ59	Senbongi lava	32.777	130.317	13±3 (F)	H99
UZ60	Older Unzen lava	32.756	130.266	197±7 (K)	M
UZ61	Older Unzen lava	32.754	130.249	ca. 300	
UZ62	Older Unzen lava	32.759	130.244	221±7 (K)	M
UZ63	Older Unzen lava	32.783	130.215	ca. 300	
UZ64	Older Unzen lava	32.780	130.237	327±11 (K)	M
UZ65	Suwaike basalt	32.694	130.202	755±36 (K)	M
UZ66	Older Unzen lava	32.709	130.223	303±10 (K)	M
UZ67	Older Unzen lava	32.773	130.218	191±8 (K)	M
UZ68	Older Unzen lava	32.703	130.280	449±14 (K)	M
UZ69	Tonosaka andesite	32.692	130.279	500±200 (K)	N88

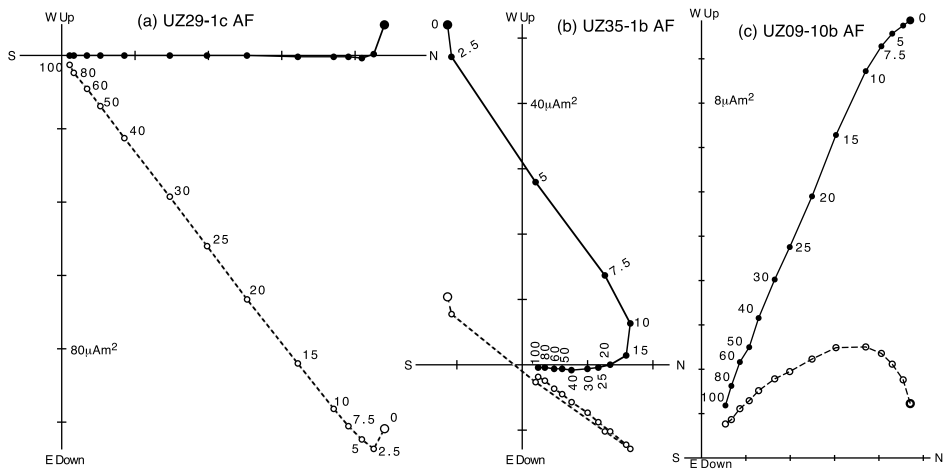


Fig. 2. Examples of progressive a.f. demagnetization, (a) of single component, (b) of double components and (c) from the excursion site.

3. Results

3.1 Lava flows

Remanent magnetizations of pilot specimens from the lava flows behaved well during progressive a.f. demagnetization. Demagnetization diagrams for specimens from most sites showed simple univectorial decay, and determining the a.f. step for blanket demagnetizations was straight forward (Fig. 2(a)). Samples from a few sites needed higher demagnetization levels, up to 40 mT, to isolate the primary magnetization, but the linear segment at high demagnetization levels was easily distinguished (Fig. 2(b) and (c)).

For individual specimens the difference between the blanket demagnetization direction and the direction calculated from linear fits to this point and those from higher demagnetization levels seldom exceeded 1 degree. Comparisons of mean directions for the blanket demagnetization and linear fitting methods were also made for 5 sites. Here the differences in mean directions were again less than 1°, and there was no systematic bias in the precision parameter (k) values between the two methods.

Two sites, UZ59 and UZ61, had scattered directions of magnetization. These sites were in outcrops consisting of several blocks, and relative movements between the blocks could not be ascertained in the field. Thus, we sampled as many of the blocks as possible to determine which, if any, were detached from the others. Unfortunately, it turned out that all of the sampled blocks had moved, and we have eliminated the results for these sites from further discussion.

Within-site magnetic directions were generally well grouped, but at a few sites, outlying data points were observed. Most likely, these points can be attributed to some part of the sampling procedure like orientation error, and it

Table 2. Paleomagnetic results. N: number of samples used/measured. Demag.: demagnetization method, AFD and ThD indicates that the direction of ChRM is calculated from the line fitting of alternating field or thermal progressive demagnetization, and numbers denote that the ChRM is represented by the vector after af demag. of the number in mT. Dec and Inc: Declination and Inclination of each site mean direction. α_{95} and k: 95% confidence angle and precision parameters, VGP Lat and Long: Latitude and Longitude of the VGP. The marks at the left indicate that the sites have special notes in the text.

							VGP		
Site No.	N	Demag.	Dec. (°)	Inc. (°)	α_{95} (°)	k	Lat. (°N)	Long (°E)	
Pyroclastic flow sites									
UZ01	8/8	ThD	−3.6	45.4	6.3	78.3	83.4	−20.7	*
UZ02	4/4	ThD				1.2			
UZ03	3/3	ThD				6.3			
UZ04	7/7	ThD-low	6.6	44.2	9.2	43.8	81.1	−91.4	
UZ10	6/6	ThD				1.9			
UZ11	8/8	ThD	−14.8	57.9	8.5	43.0	76.7	70.2	
UZ12	6/6	ThD				1.5			
UZ14	7/7	ThD	8.6	45.5	5.0	145.6	80.5	−103.9	†
UZ15	5/5	ThD				1.3			
UZ17	9/9	ThD	59.0	63.5	3.9	171.9	43.5	−173.1	*
UZ18	8/8	ThD	5.4	17.2	4.8	132.7	65.6	−62.7	*
UZ22	9/9	ThD				2.5			
UZ23	5/5	ThD				1.6			
UZ24	6/6	ThD	−1.1	50.2	2.9	548.0	88.0	−22.0	
UZ25	7/7	ThD	−1.4	46.7	11.1	30.4	85.0	−35.3	
UZ30	9/9	ThD				1.1			
UZ33	6/11	ThD	−13.3	57.8	10.1	44.6	77.8	71.9	
UZ39	11/11	ThD				1.1			
UZ43	8/8	ThD-low	1.0	37.4	7.2	71.7	78.1	−54.3	
Lava sites									
UZ05	8/8	AFD	12.8	47.1	1.9	815.6	78.1	−120.9	†
UZ06	7/7	AFD	−0.6	36.7	3.7	264.6	77.7	−47.0	
UZ07	8/8	AFD	18.1	57.4	5.5	103.0	74.4	−164.4	
UZ08	6/6	AFD	24.9	55.9	3.3	401.2	69.2	−156.9	
UZ09	11/11	AFD	−72.6	−21.0	2.6	305.4	8.3	21.6	
UZ13	7/7	AFD	22.6	46.6	11.2	29.9	69.9	−131.5	
UZ16	5/5	ThD	24.0	49.2	5.6	189.1	69.4	−138.5	
UZ19	7/8	20	2.9	40.5	2.1	792.5	80.1	−65.4	
UZ20	8/8	25	−33.9	50.7	2.4	521.9	61.4	47.0	
UZ21	7/8	15	−25.1	16.8	3.8	259.0	56.5	−0.2	
UZ26	8/8	20	−29.8	44.8	2.3	585.7	63.4	34.4	
UZ27	8/8	25	−47.0	49.8	5.8	91.4	50.3	50.3	
UZ28	8/8	20	−6.5	66.3	2.3	591.3	73.3	115.2	
UZ29	9/9	7.5	−2.3	47.7	3.7	196.2	85.6	−22.5	
UZ31	9/9	AFD	22.9	46.0	8.8	35.3	69.5	−130.5	
UZ32	8/8	20	−15.0	62.2	2.5	481.9	74.1	87.1	†
UZ34	8/9	25	−3.7	29.3	2.3	557.3	72.5	−37.7	
UZ35	7/8	40	8.0	39.5	2.9	429.3	77.4	−86.0	
UZ36	9/9	50	17.0	61.8	1.9	755.9	73.2	177.8	
UZ37	8/8	10	18.6	59.6	1.9	814.7	73.3	−172.4	
UZ38	8/8	5	19.8	66.9	3.5	295.0	67.7	165.6	
UZ40	8/8	15	11.6	53.9	2.6	452.8	80.2	−152.8	
UZ41	6/6	20	39.9	60.0	3.8	308.7	57.3	−165.8	
UZ42	8/8	20	−6.7	48.4	4.9	129.4	83.3	11.2	
UZ44	11/11	25	0.0	59.1	5.3	74.2	82.9	130.3	
UZ45	7/7	40	−4.6	40.5	3.1	375.2	79.6	−25.7	
UZ46	8/9	40	2.1	47.2	1.2	2125.7	85.3	−72.6	
UZ47	8/8	25	11.2	55.3	2.9	377.3	80.3	−161.2	‡
UZ48	6/6	15	19.8	55.2	2.8	592.0	73.4	−155.5	‡
UZ49	8/8	15	2.6	46.6	2.3	606.1	84.6	−75.1	

Table 2 (continued).

							VGP		
Site No.	N	Demag.	Dec. (°)	Inc. (°)	α_{95} (°)	k	Lat. (°N)	Long (°E)	
Lava sites (continued)									
UZ50	9/9	15	−0.1	48.9	2.6	389.2	87.1	−48.0	
UZ51	9/9	20	−13.1	30.2	3.5	220.2	69.7	−11.0	
UZ52	8/9	15	−7.7	46.4	3.2	293.3	81.6	5.0	
UZ53	8/9	10	−4.8	43.7	2.4	446.7	81.6	−18.4	
UZ54	8/8	50	−1.1	31.0	3.9	201.5	73.9	−45.9	
UZ55	8/8	40	−9.8	61.5	1.7	1115.3	77.4	95.2	†
UZ56	8/8	20	−0.5	70.4	3.1	319.6	68.2	129.5	†
UZ57	7/7	40	−5.5	33.2	2.0	870.8	74.6	−29.7	
UZ58	6/8	20	−2.1	39.7	3.4	394.7	79.6	−38.8	
UZ59	10/10	40				2.5			
UZ60	9/9	40	−0.6	46.7	3.5	217.2	85.2	−43.4	
UZ61	9/9	50				3.6			
UZ62	8/8	40	8.5	49.9	2.1	670.9	82.5	−126.1	
UZ63	10/10	7.5	−3.2	50.9	1.1	1901.5	87.0	17.5	
UZ64	7/7	10	−6.4	54.4	2.3	713.0	84.3	64.0	
UZ65	8/8	20	18.0	54.1	1.8	1000.8	74.9	−152.1	
UZ66	8/8	20	−1.2	62.4	5.3	111.4	78.9	125.7	
UZ67	8/8	40	17.9	56.4	1.8	976.7	74.8	−160.7	
UZ68	8/8	10	6.3	54.4	5.0	123.5	84.3	−164.5	
UZ69	7/7	25	0.0	43.5	2.5	599.0	82.7	−49.7	

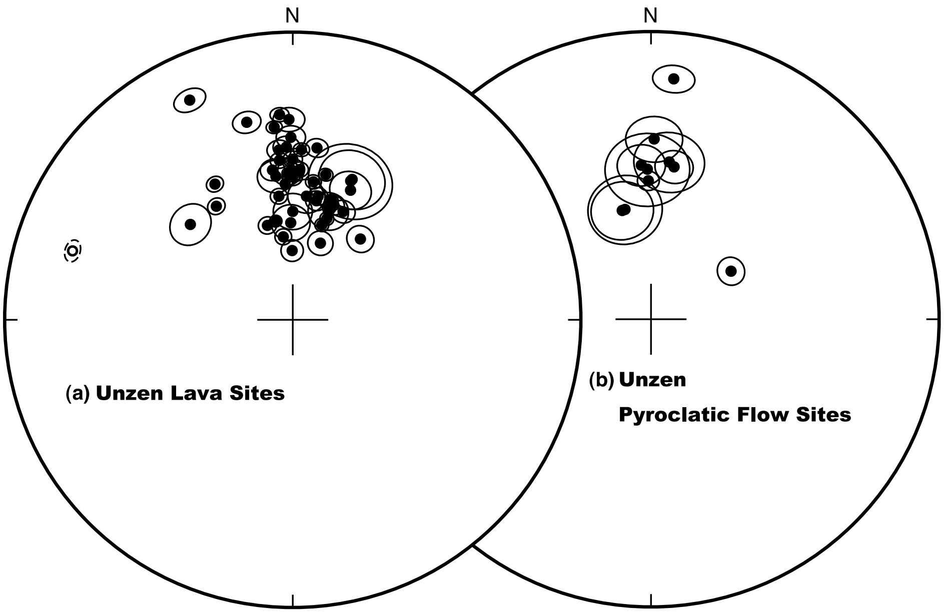


Fig. 3. Paleomagnetic site mean directions of (a) lava flow sites and (b) pyroclastic flow sites. All directions are on the lower hemisphere. Ellipses around symbols indicate the 95% confidence limits.

is very difficult to completely eliminate such errors. The criteria used to classify outliers were taken from McFadden (1982), and these data points were discarded before calculation of the site means. Data for eight sites contained such outliers, and, with the exception of one site, had only one outlier each.

The paleomagnetic statistics for each site are tabulated in Table 2, and the site-mean directions are illustrated in Fig. 3(a). Out of 50 sites, we obtained 48 site means with $k > 20$; concentrations of the magnetic directions were mostly good with precision parameters commonly exceeding 300.

3.2 Pyroclastics flows

Pyroclastic flows (pcfs) were initially sampled because we expected them to have settled at high temperatures and to have retained stable *in situ* paleomagnetic directions.

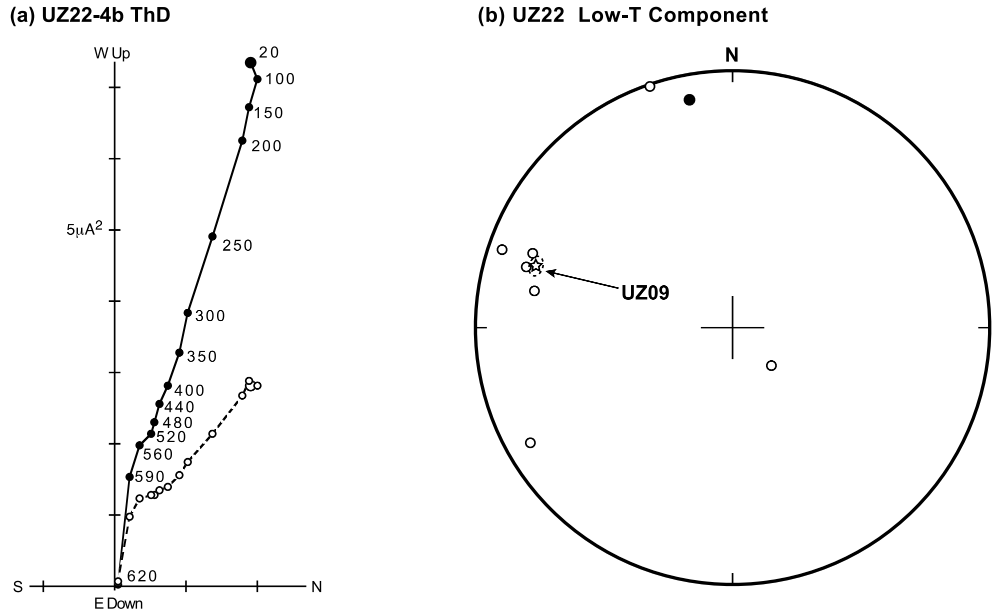


Fig. 4. (a) Orthogonal demagnetization diagram of a sample from site UZ22 in a pyroclastic flow, which is correlated with the UZ09 Senbongi excursion site, showing that it has two components. (b) The directions of a low-temperature component, along with the site mean direction of UZ09.

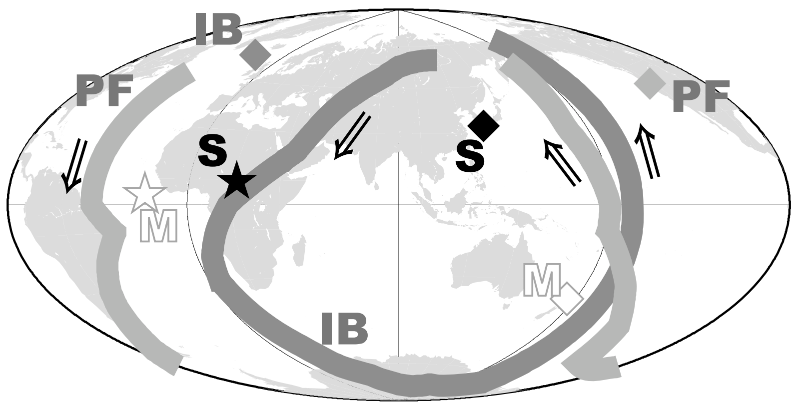


Fig. 5. VGP position of the Senbongi excursion (S), superimposed on the VGP position of the Mamaku excursion (M) and VGP-paths of the Iceland Basin (IB) and Pringle Falls (PF) excursions. Diamonds indicate the site locations.

Samples from all of the pcf sites therefore were subjected to progressive thermal demagnetization. We believed that even if the settlement temperature was less than the Curie temperature of the constituent magnetic minerals we should be able to isolate a ChRM. Data for many sites, however, showed scattered directions with $k < 10$ for both high and low temperature ranges, indicating that the 'pyroclastic flow' deposits were near the ambient temperature at the time of deposition. In this case the term 'volcanic breccias' is perhaps more appropriate for these rocks, although we will still refer to them using their field name of 'pyroclastic flows'; further discussion of this problem was presented by Tanaka *et al*. (2004). Details of the demagnetization characteristics for these rocks were also described in this earlier paper.

Within pcfs it is often difficult to distinguish blocks that were hot at the time of deposition from cold ones based on field observations alone, because the cold material mixed in could have been an earlier product of the same eruptive series. Apparently the pcf sampled at site UZ33 was deposited with both hot and cold blocks; magnetic directions for 6 samples form a rather tight cluster while 5 other samples from the site have widely scattered directions. We were at first afraid that we might find many sites like UZ33, since the rejection criteria of directions would be subjective for such sites, but in all other cases the precision parameters were clearly divided between sites with clustered or scattered directions.

The means for only 10 sites had $k > 20$, and the precision parameters generally indicated more scattered data than for the sites in lava flows. This is probably due to the movement of cobble blocks before or at the time of sampling. The statistics for site-mean directions for the pcfs are listed in Table 2 and are illustrated in Fig. 3(b).

4. Discussion

4.1 Senbongi excursion

As expected from the lava flow ages, all but one of the site-mean directions was of normal polarity, i.e., the corresponding VGP latitudes were greater than 50°N. The ex-

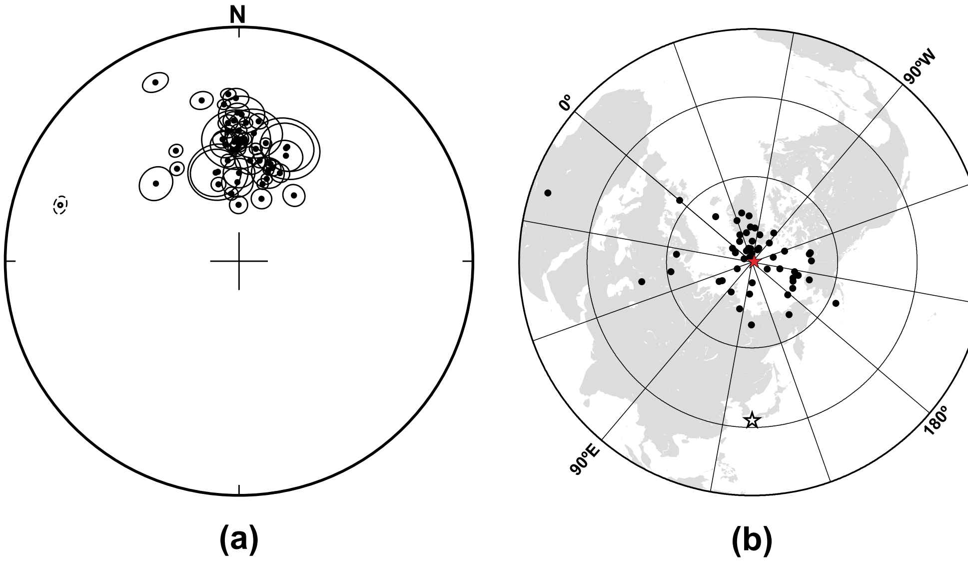


Fig. 6. Paleomagnetic direction (a) and VGP (b) plots of the Unzen sites. Duplicated sites are excluded as described in the text. Solid and open stars in (b) are the mean VGP excluding the excursion site, and the location of Unzen volcano, respectively.

ception was the direction for site UZ09 which has a VGP latitude as low as 8.3°N. This intermediate direction/VGP appears to have recorded an excursion of the geomagnetic field, although we could not find another outcrop within the same lava flow to confirm that it is not due to a large block rotation of the sampling site. The site is on the edge of a gentle ridge that seems to have been formed by the lava flow itself, so there is no possibility of the sampled rocks having fallen off this higher part. Other evidence supporting the interpretation of an excursion is the paleomagnetic direction from site UZ22 in a pcf. This flow is stratigraphically close the UZ09 lava flow, and the two are thought to have been erupted at about the same time. Progressive thermal demagnetizations show that most of the samples from site UZ22 have two magnetic components. The directions of these components tend to be widely scattered, but there is a cluster of data points similar to the UZ09 mean direction (Fig. 4). These relationships could be explained if (1) the UZ09 lava flow and UZ22 pcf were emplaced during the same eruptive episode, (2) several blocks within the UZ22 flow were deposited at temperatures around 350°C, and (3) the episode occurred at the time of a geomagnetic excursion. Hereafter we will call this excursion the Senbongi excursion.

The K-Ar age for the UZ09 lava flow is 197±17 ka (Matsumoto *et al.*, in prep.). Wollin *et al.* (1971), Ryan and Flood (1972), and Kawai *et al.* (1972) initially reported a geomagnetic excursion or short event at about 200 ka from marine or lacustrine sediment cores. Champion *et al.* (1988) reviewed the geomagnetic events within the Brunhes chron and referred to the event at 200 ka as the Jamaica/Biwa I event. Herrero-Bervera *et al.* (1994) produced a ^{40}Ar/^{39}Ar age of 218±10 ka on a tuff layer proximal to a geomagnetic event they called the Pringle Falls event that has been found in a number of lake deposits in the western USA. Among other reports of a ∼200 ka excursion is Channell *et al.*'s (1997) documentation of what they call the Iceland Basin event from detailed paleomagnetic and oxygen isotope logs of sediment APC cores retrieved off Iceland (ODP Site 983). Channell (1999) argues that the age of the Iceland Basin event (189–186 ka) is distinguishable from that of the Pringle Falls event, and that there might be two separate events, although they could not find clear evidence of the Pringle Falls event in the Iceland Basin cores. In addition, he argued that the Iceland Basin records and dates of the ∼200 ka excursion are so much improved that it should be referred as the Iceland Basin (IB) event. As the relation between the IB and Pringle Falls (PF) excursions is not well established, we will refer to the excursion at ∼200 ka together as the name of IB/PF event.

Assuming the existence of two events at ∼200 ka, it is not clear which event the Senbongi excursion correlates with. The age of the Iceland Basin event is closer than that of the Pringle Falls event to the age of the Senbongi excursion, although the Pringle Falls and Senbongi ages are similar within error limits. In either case, the Senbongi excursion appears to be well correlated with the IB/PF event.

The VGP for the Senbongi excursion is located at 8.3°N, 21.6°E in central Africa, and is shown in Fig. 5 along with the schematic VGP paths for the IB (Channell, 1999) and PF events (Herrero-Bervera *et al.*, 1994). Although the meaning of an intermediate VGP location during an excursion should be treated with caution, the Senbongi VGP falls almost exactly on the VGP path for the IB event and not on the PF VGP path perhaps supporting the correlation.

Laj *et al.* (2006) studied four sediment cores from the North Atlantic Basin and South China Sea, and discussed in detail the VGP paths calculated from all of the available paleomagnetic data reported for the IB event. In addition to their own data they identified three other reliable data sets from among the published records, including a record from Lake Baikal (Oda *et al.*, 2002). The VGP paths for these data sets also pass through central Africa in agreement with the Senbongi VGP. Although the comparison of intermediate VGP locations over large distances might be invalid using the dipole hypothesis, the agreement between the sites in East Asia (Lake Baikal, South China Sea, Senbongi) would support the correlation of the observed excursions

It is interesting to note that another report of the IB/PF event from volcanic rocks seems to have similar coincidence, but to the PF event. The excursional magnetic direction of the Mamaku ignimbrite on the North Island of New Zealand was first reported by Cox (1969a). Shane *et al.* (1994) and Tanaka *et al.* (1996) confirmed the excursion, and dated it at 0.23±0.01 Ma by fission track, and at 0.22±0.01 Ma by $^{40}Ar/^{39}Ar$ methods, respectively. McWilliams (2001) compared the PF and Mamaku VGPs, and concluded that the two records were of a single event. Moreover, the Mamaku ignimbrite VGP comes close to the PF VGP path, although there is an offset of about 30°. This offset is within normal secular variation on the geomagnetic field, so the conclusion of McWilliams (2001) appears appropriate. Such coincidences may indicate that aborted reversals at IB/PF time flipped the dipole of dominant intensity.

4.2 Averaged paleomagnetic direction and the dispersion

Combining the site-mean data for both lava flows and pcfs, we obtained mean ChRM directions for 58 out of 69 sites with $k > 20$. Although a cut-off threshold of $k = 20$ might be considered too low, this threshold was not designed for calculating mean directions to represent paleosecular variation, but, as we will see later, for discussing the statistical character of the data set.

Samples at some sites were deliberately collected from the same geological unit to test its classification. Tanaka *et al.* (2004) discussed the details of these tests and concluded that (1) the pcf at site UZ14 (Mutsugi pcf) was erupted from the same volcanic episode as the lava flow at site UZ05 (Shichimenyama lava flow), (2) two sites in the north lobe of the Fukkoshi lava flow (UZ47 and UZ48) have barely distinguishable paleomagnetic directions, and (3) two sites (UZ32 and UZ55) in the south lobe of the Fukkoshi lava flow have similar directions although the direction for a third site (UZ56) is different. Since sites UZ14 and UZ05, and sites UZ32 and UZ55, have statistically indistinguishable mean directions, these directions should not be thought of as independent samples of the secular variation. We have simply chosen the site means with smaller α_{95} values from each pair (UZ05 and UZ32) to best represent the ambient field directions for these flows. Although sites UZ47 and UZ48 have similar mean directions, the directions are statistically distinguishable because of their small α_{95} values. Since the age of magnetization acquisition is most likely the same at both sites, we select the direction for site UZ48 (smaller α_{95}) as the most representative. We also exclude the direction for the recent pcf at site UZ01 and substitute the present geomagnetic field direction ($D = -6.4°$, $I = 47.1°$) for Nagasaki City (National Astronomical Observatory Japan, 2004).

Sites UZ17 and UZ18 are in different parts of the same pcf. Their mean paleomagnetic directions, however, are quite different being ∼50° apart from one another. Thus, we discard these two sites from any further discussion.

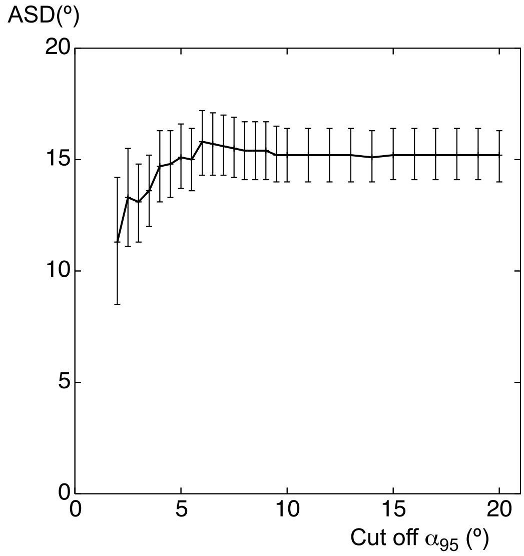
Another problematic result is for site UZ21 that is from the same geological unit as site UZ06 (Tanaka *et al.*, 2004), but has a significantly different direction (Table 2; Fig. 3). Two explanations are possible for the lower inclination (∼20°) of the UZ21 mean direction: Either (1) slump movement of a large block including site UZ21 has occurred, or (2) two different lava flows were sampled. Site UZ06 was collected from the top of a lava dome, and UZ21 is located on its eastern flank. A 30° tilt about a horizontal axis to the ESE is needed to move the UZ06 direction into coincidence with the UZ21 direction. Large-scale slump movements in the area, however, are to the east and would tilt the UZ06 block westward, thus moving the UZ06 direction to the east rather than to the UZ21 direction. Therefore, the UZ06 and UZ22 sites are most likely in different lava flows, and we treat the site means as two separate records of PSV.

The 53 individual site-mean directions and corresponding VGPs are plotted in Fig. 6(a) and (b), respectively. In order to eliminate unreliable data, we have initially set an upper limit for α_{95} values at 10°, and will later look at the effects of changing this limit. Excluding means with $\alpha_{95} > 10°$ and the excursion direction (UZ09), the remaining 49 site means give an overall mean direction of $D_m = 0.4°$, $I_m = 49.8°$ with $\alpha_{95} = 3.7°$ and $k = 31.3$. This observed direction agrees well with the expected direction calculated from a geocentric axial dipole field with an expected inclination of 52.1°. The mean for the 49 VGPs is at 88.7°N, 87.5°W ($A_{95} = 4.1°$, $k = 25.3$) and is statistically indistinguishable from the geographic pole. No far-sided or near-sided effects of the VGP dataset are observed. The angular standard deviation (ASD) for the mean pole is 16.3° ($-2.6°/+2.8°$), with the error calculated after the method of Cox (1969b). ASD values for Japan will be discussed in greater detail in the next section after compiling other relevant data available in the scientific literature.

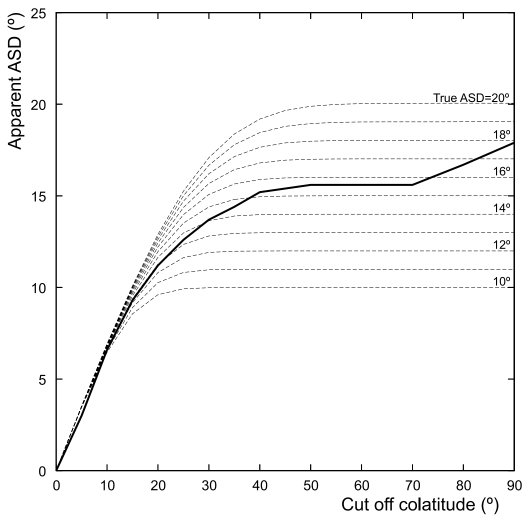
4.3 Brunhes PSV in Japan

Studies of the stochastic paleosecular variation for Japan were few in the early years of Japanese paleomagnetism, in spite of the fact that Japanese paleomagnetists made significant contributions to a number of related fields. The first paleomagnetic investigations to estimate the ASD for Brunhes-aged rocks in Japan were made by Heki (1983) with data for 29 lava flows in the Higashi Izu and Kagoshima regions that are separated by about 800 km. Since then, five more papers reporting Bruhnes paleomagnetic directions from volcanic rocks have been published (Tsunakawa and Hamano, 1988; Ishikawa and Tagami, 1991; Otake *et al.*, 1993; Morinaga *et al.*, 2000; Tanaka and Kobayashi, 2003). This makes available a total of 122 Brunhes-aged VGPs with $\alpha_{95} < 20°$ to which we add 51 VGPs for a combined total of 173 VGPs; we will refer to this combined total as the JB06 dataset.

In calculating a mean pole and ASD, it is common practice to set two limits on the input data, the first being a maximum threshold for the site-mean α_{95} values and the second being a maximum threshold for colatitude (θ_c) above which the VGP is assumed to be part of a field polarity excursion or transition rather than normal PSV. To examine the effect of changing the α_{95} maximum cut-off value we graphed it vs. ASD in Fig. 7(a). Although ASDs decrease with maximum α_{95} values less than ∼6°, this appears to be a statistical



(a)



(b)

Fig. 7. ASD variation of JB06-a10 dataset with changing cutoff (a) α_{95} and (b) θ_c. Dotted lines in (b) indicate the change of apparent ASD for Fisher distributions with true ASD values denoted by the lines.

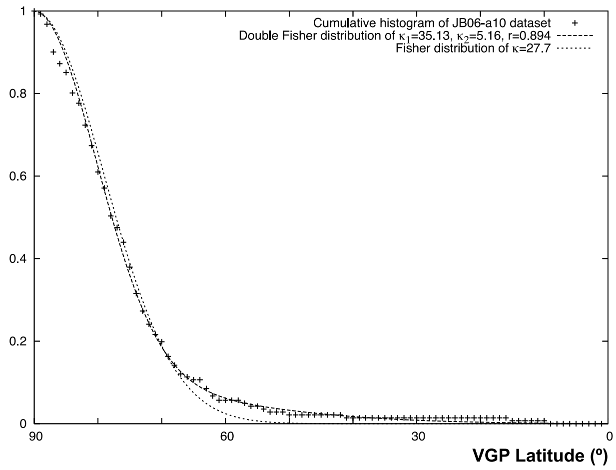


Fig. 8. Cumulative histogram of the JB06-a10 dataset and optimum single and double Fisher distributions.

artifact as the ASD for an α_{95} cut-off value of 10° is statistically similar to all of the other ASDs. Thus, we have set the α_{95} cut-off value to the commonly used 10° which reduces the number of VGPs in the dataset to 150; we will call this dataset the JB06-a10 dataset.

The greatest problem in calculating an accurate ASD is determining the correct θ_c value. The calculated ASD is proportional to the arbitrarily chosen θ_c value, but if we use all VGPs the ASD strongly depends on the presence of a few intermediate VGPs. Setting θ_c to 50° as is commonly done, the ASD for the JB06-a10 dataset is 15.2° ± 1.2° ($N = 148$). It should be noted that there are 3 VGPs (2%) having latitudes between 50° and 55°, while only 0.5% is expected for the corresponding Fisherian distribution, and this tendency is often seen in other PSVL studies as well (Shibuya *et al.*, 1995). The calculated ASD with $\theta_c = 50°$ apparently meets the standard models of PSV (e.g. McElhinny and McFadden, 1997), but we will now consider the meaning of the ASD in greater detail.

Figure 7(b) illustrates the apparent change in ASD versus θ_c for the JB06-a10 dataset (solid curve). Also shown are values for modeled Fisherian distributions with true ASDs ranging between 10° and 20° (dashed curve). Assuming the observed distribution is Fisherian, it is expected that the solid curve would follow on one of the dotted curves. As this is not the case for the JB06-a10 dataset (the solid line crosses dotted lines of ASD=15° to 13° as θ_c decreases from 50° to 20°), the observed distribution is not Fisherian even after omitting the outliers.

Several methods have been proposed to avoid the problem of arbitrarily assigning θ_c to a given dataset. Vandamme (1994) developed an algorithm to determine θ_c in which the VGPs farthest from the current mean are removed until the dataset fulfills a certain criterion. The problem with this algorithm, however, is that the reverse calculation, starting with a few VGPs at high latitudes and adding on until the dataset fails the criterion, often gives a different θ_c value. In practical terms, the algorithm is not robust enough to handle the small changes caused by a few critical VGPs. Another problem with this algorithm is that Vandamme assumes that the input dataset follows a Fisherian distribution plus a uniform distribution. The nature of the observed distribution itself, however, is an open question in PSV studies.

Shibuya *et al.* (1995) proposed characterizing PSV by fitting a double Fisherian distribution (sum of two Fisherian distributions) to the cumulative histogram of the given dataset. They assumed that geomagnetism has two periods of different stability, normal and excursional, and that VGPs of each period have Fisherian distributions with different κ. Applying this method to the JB06-a10 dataset gives the precision parameters of the two Fisherian distributions as $\kappa_1 = 35.13$ and $\kappa_2 = 5.16$, and the ratio of 0.894:0.106 (Fig. 8). The κ_1 value corresponds to an ASD value of 13.7°, and it is interesting to note that this value is as low as those for other areas in the Pacific region (Shibuya *et al.*, 1995). This ASD value for Japan is lower than the one given by Shibuya *et al.* (1995), partly because the new dataset is larger and restricted to the Brunhes chron, but moreover because they used a single Fisherian distribution as there were few intermediate VGPs in the dataset available at that time. Parametric bootstrap simulations of the distribution indicate that the calculated ASD is not stable, particularly when intermediate VGPs are scarce. It is also understood that a greater number of parameters to determine introduces greater error in each of the parameters.

In setting a fixed θ_c value for datasets from around the world, the calculated ASDs are still a relatively robust measure of the scattering. The strict meaning of these ASDs, however, remains unclear. Perhaps we need to find a more appropriate distribution for PSVL than that proposed by Fisher, as well as a corresponding statistical parameter representing the dispersion.

5. Summary

(1) Fifty reliable paleomagnetic directions were obtained for lava and pyroclastic flows from Unzen Volcano. Ages for many of these flows have been determined using the K-Ar method, and the undated flows have been stratigraphically related to the dated flows by field observations. All flows were deposited within the Brunhes chron.

(2) An excursion, named the Senbongi excursion, was identified from an intermediate VGP for the Senfongi lava flow dated at 197±17 ka. The resolution of the age for the Senbongi excursion is not high enough to correlate it with either the Iceland Basin or Pringle Falls event. The coincidence of the Senbongi VGP with the Iceland Basin record likely supports their correlation.

(3) The Unzen dataset increases the Brunhes PSVL dataset for Japan by a factor of 1.5 times. The ASD calculated using the conventional cutoff for VGPs at 50° latitude is $15.2^\circ \pm 1.2^\circ$ ($N = 148$). The distribution of data points is better fitted by a double Fisherian distribution which gives an ASD of 13.7°. The distribution, however, appears to depart from a Fisherian distribution, and this may be the reason why the ASDs calculated from the two different methods are discordant

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