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Paleomagnetism of the late Quaternary Ontake Volcano, Japan: directions, intensities, and excursions

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Study of paleosecular variation was carried out to mostly andesite lavas from the late Quaternary Ontake Volcano which have detailed stratigraphy and accurate radiometric ages. Among 42 sites, some of the results from lava successions were combined due to possible equivalent ages, remaining 35 sites. After excluding two low latitude VGPs, angular dispersion of 15.6° was obtained for a period which is accurately confined between 20 ka and 90 ka. The obtained angular dispersion is not different from the typical value for the last 5 my, and this is not surprising if we consider that the global paleointensity was not necessarily low and rather oscillatory during the period of 40–100 ka which precedes the global low in 20–40 ka. Two low latitude VGPs from 48 ka lava (41.9°N, 196.2°E) and 80 ka lava (15.9°N, 183.3°E) indicate existence of excursions in Japan during the latest Pleistocene. Preliminary paleointensity experiments indicate that the 80 ka excursion is accompanied by a low paleointensity of about 5 μT while the 48 ka one is not. These two excursions are probably related to those reported previously not only from the Ontake Volcano and its proximity but also from other several sites in Japan, although they were not conclusive. The 48 ka excursion probably correlates to the Laschamp excursion. This is consistent with the fact that the VGP position from the 48 ka lava comes to the central Pacific region, similar to those from the Laschamp excursion found in New Zealand. Possible correlation of the 80 ka excursion is the one from Norwegian-Greenland Sea and Arctic Ocean, which are stratigraphically between the Laschamp and the Blake excursions.

Key words: Paleosecular variation, paleointensity, Ontake Volcano, excursion, Laschamp, Blake.

1. Introduction

Paleosecular variation (PSV) from lavas has often been used as a statistical indication of the past geodynamo activity. Angular standard deviation (ASD) is usually used as a measure of angular dispersion in the positions of the virtual geomagnetic pole (VGP). One of the established features of the past geomagnetic field is that ASD of VGP becomes larger when observed at higher latitude (McElhinny and McFadden, 1997).

Although the standard latitude variation curve of ASD is well established for the recent geological time, its dependency on the longitude of the observation site is still controversial. Hypothesis of the Pacific Non-dipole Low is a long-standing issue (ex., Shibuya *et al.*, 1995; McElhinny *et al.*, 1996). There are some anisotropic PSV models which propose longitude dependent ASD (ex., Tsunakawa, 1988; Constable and Johnson, 1999). Hence, it is always important to add a new study from wide area of the world (ex., Yamamoto *et al.*, 2002). This paper reports a PSV study from 41 lavas from Japan of late Quaternary age, together with preliminary results of paleointensity experiments made to several selected lavas.

Quite a few excursions have been reported in the Brunhes chron (Lund *et al.*, 1998), although there are only few of them which have been established as a global feature of the geomagnetic field. Identification of an excursion in lava flows would be a strong evidence to its existence because possibility of data artifacts is much smaller in the remanence of volcanic rocks which originates from a thermoremanent magnetization (TRM). This study also reports excursions found from two lava flows of 48 ka and 80 ka.

2. Geology and Sampling

The Ontake Volcano is a member of the Norikura Volcanic Zone in central Japan, and forms a composite volcano reaching the maximum altitude over 3 km. Detailed summary of stratigraphy and petrology was given by Yamada and Kobayashi (1988). Volcanic products of the Ontake Volcano are mostly lavas and pyroclastics of andesite including minor rhyolite, dacite and basalt. Its edifice consists of two compound volcanoes with clear erosional gap between them, which are called the Older and Younger Ontake. Prolonged cessation of volcanism has been suggested between the two volcanoes, and a recent geochronological study using K-Ar dating by Matsumoto and Kobayashi (1995, 1999) revealed the detailed history of the Older and Younger Ontake. The Older Ontake Volcano was formed during the period between 750 and 420 ka. Long period of subdued volcanism succeeded lasting over 300 ky, and the edifice of the volcano was heavily eroded leaving the total volume of volcanic products amounting to about 40 km^3. At about 80–90 ka volcanism restarted to form the Younger Ontake Volcano which added volcanic products of another 40 km^3 and finally formed the

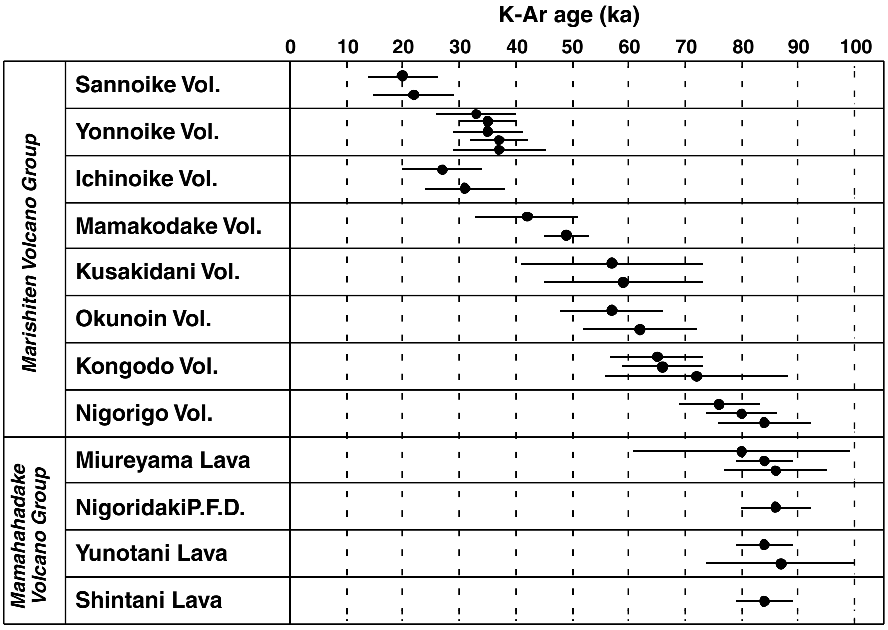

Fig. 1. Highly correlated radiometric age and stratigraphy for the lava flows from the Younger Ontake Volcano. This figure was reproduced from figure 5 of Matsumoto and Kobayashi (1995) with permission from Elsevier Science, although a minor correction was made in stratigraphy. In the original figure, stratigraphy of two volcanoes was erroneously placed. Stratigraphic position of Yonnoike Volcano is higher than Ichinoike Volcano although inconsistent relation of the K-Ar ages is observed between them. Note that within a specific volcano the data points were ordered by age because no stratigraphic relation is known among each lava flows.

present-day shape of stratovolcano.

Activity of the Younger Ontake Volcano started with eruption of huge volume of rhyolite pumice-falls, resulting in the formation of an extensive tephra layer called "Pm-I" which covers a wide area of central Japan. Eruption of dacitic products followed and resulted in the formation of a composite volcano. This earlier stage of the Younger Ontake is called Mamahahadake Volcano Group. Next stage of volcanism started with an abrupt change of petrology and resulted in the formation of series of small stratocones of andesitic products which are overlapped each other and make up the summit of the present Ontake Volcano. This later stage is called Marishiten Volcano Group. Activity of the Marishiten Volcano Group ended at about 20 ka, and following inactive period includes only superficial phenomena with the most recent phreatic explosion of 1979. Matsumoto and Kobayashi (1995) gave an excellent correlation between the newly obtained K-Ar dating and the volcano-stratigraphy as shown in Fig. 1. This figure was reproduced from Matsumoto and Kobayashi (1995) with a minor correction because stratigraphic order of two volcanoes was erroneously placed in the original figure. Stratigraphic position of Yonnoike Volcano is higher than Ichinoike Volcano although inconsistent relation of the K-Ar ages is observed between them. Nevertheless, accuracy of K-Ar ages are well illustrated in Fig. 1.

Samples collected in this study are from andesite lavas from the Younger Ontake which are found at both summit and mountainside. Sampling localities and associated K-Ar ages are included in Table 1 which summarizes all paleomagnetic results in this study and the K-Ar ages by Matsumoto and Kobayashi (1995). Although most of the K-Ar ages are not necessarily from the specific flows collected in this study, they should represent fairly accurately the ages of the lavas collected.

A portable drill was used to collect core samples and a sun compass was used for orientation. Difference of magnetic azimuth, used when sun is not available, from the sun azimuth is usually less than 2–5°. Any tilt correction was not made to the measured remanence directions because no local tectonic disturbance was observed throughout the sites sampled.

3. Measurements of Paleodirections

Six to eight cores were usually collected at each site, and alternating field (AF) and thermal demagnetizations were progressively applied to at least one sample for each site. When determination of the characteristic remanence is straightforward, only AF demagnetization was applied to the rest of the cores and progressive demagnetization was stopped when the stable component was confirmed as a set of data pointing to the origin on the orthogonal plot.

Most samples have a stable characteristic remanence with only moderately small secondary components which are easily cleaned by AF or thermal demagnetization. Typical orthogonal plots of AF and thermal demagnetizations are shown in Fig. 2(a,b) and (c,d), respectively.

Although defining a characteristic remanence is straightforward for most lavas, there were seven problematic sites which apparently suffered from lightning strikes. Possible lightning strikes at these sites are easily known by very large NRM intensities, and this is consistent with the fact that the site localities were at the summit of high altitude. In some samples, the remanence direction moved along a great circle with progressive demagnetization as shown in Fig. 2(e), and the characteristic remanence (Chrm) was never revealed by both AF and thermal methods. In most cases, however, the

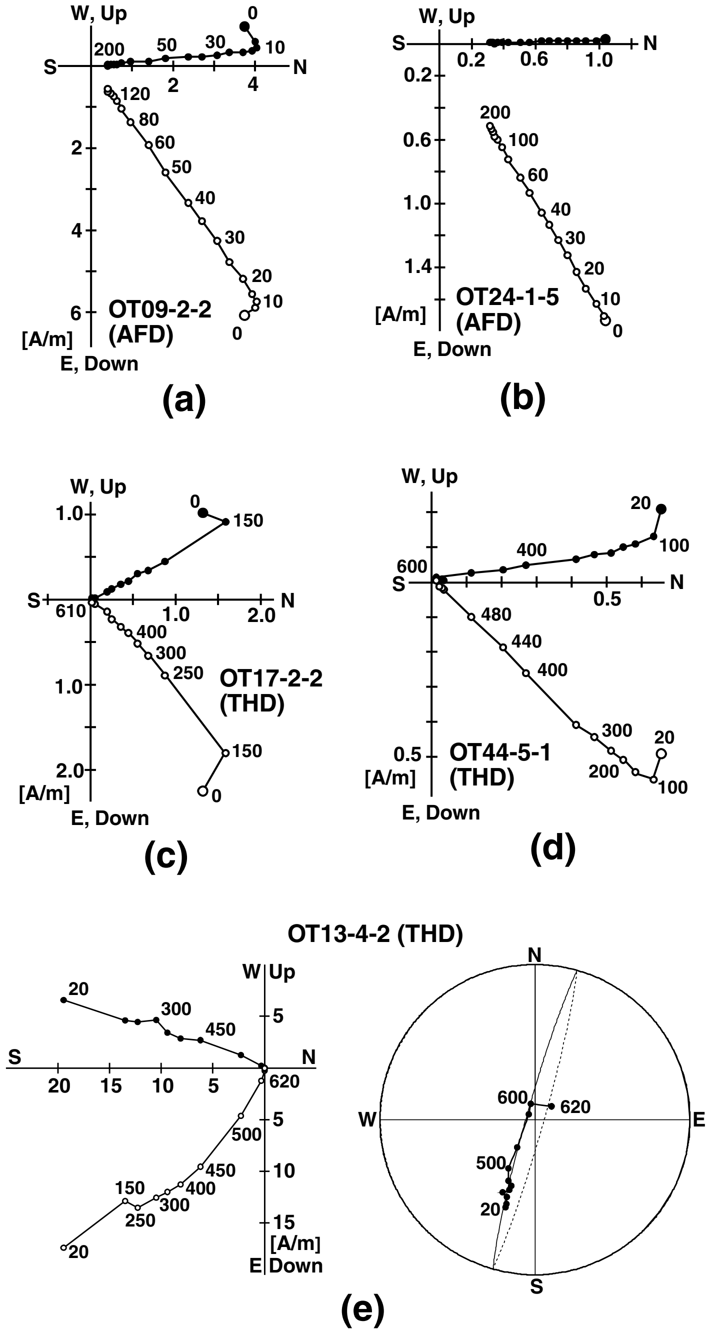

Fig. 2. Typical orthogonal plots of progressive AF (a,b) and thermal (c,d) demagnetizations. Samples are andesite lava except for OT24 (b) which is a rare case of a rhyolite lava. An example of orthogonal plot and corresponding equal area plot of thermal demagnetization are shown in (e) for a problematic site which apparently suffered from a lightning strike. Application of the method of McFadden and McElhinny (1988) to the combined great circles and linear data was successful in most cases.

site mean direction was successfully obtained from the combination of the great circles and linear data by the method of McFadden and McElhinny (1988). Exceptions were two sites in which the results were finally rejected due to a large error ($\alpha_{95} > 20°$).

Intermediate directions were found at three sites from two lava flows of 48 ka and 80 ka. Representative orthogonal plots of AF and thermal demagnetizations are shown in Fig. 3 for the 48 ka (a,b) and 80 ka (c–f) lavas. Stability of the remanence to both AF and thermal demagnetizations indicates the primary origin of these anomalous paleodirections. There are three exceptions among 19 samples from the 80 ka lava, one of which is shown in Fig. 3(f). Inconsistent remanence direction of OT33-8-1 is probably of secondary origin because of abnormally high remanence intensity and its rapid decrease with progressive AF demagnetization. This is also supported by the fact that the three inconsistent remanence directions were found from a limited part of the outcrop. Hence, these three directions were discarded.

Equal area plot of sample directions are shown in Fig. 4 for the 48 ka and 80 ka lavas, where the larger circle indicates the site mean direction. The anomalous paleodirection of the 48 ka lava is certain because they were obtained from two distinct sites which are 200 m apart. The paleodirec-

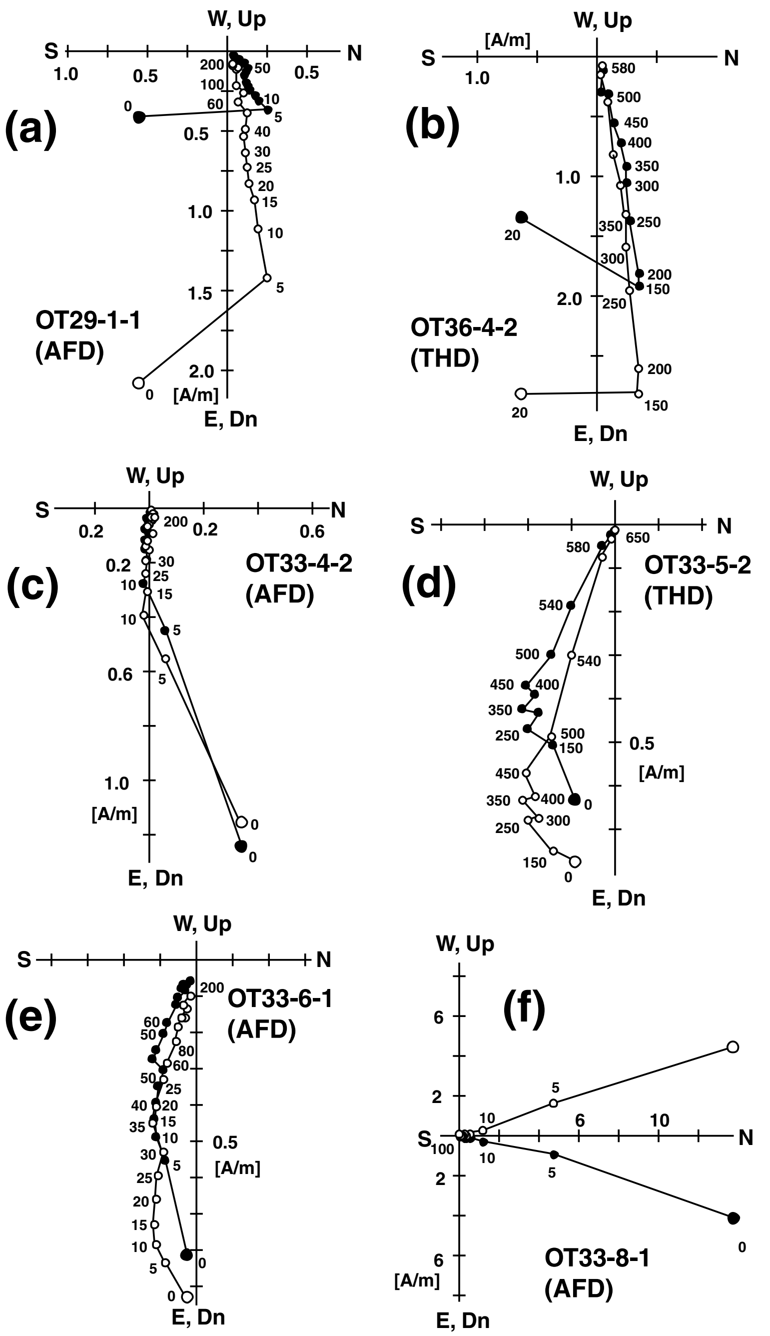

Fig. 3. Examples of orthogonal plot of progressive thermal and AF demagnetizations to the 48 ka (a,b) and 80 ka (c–f) lavas, which give intermediate paleodirections. The remanence of OT33-8-1 shown in (f) was judged to be of secondary origin due to its rapid decrease and much stronger NRM intensity.

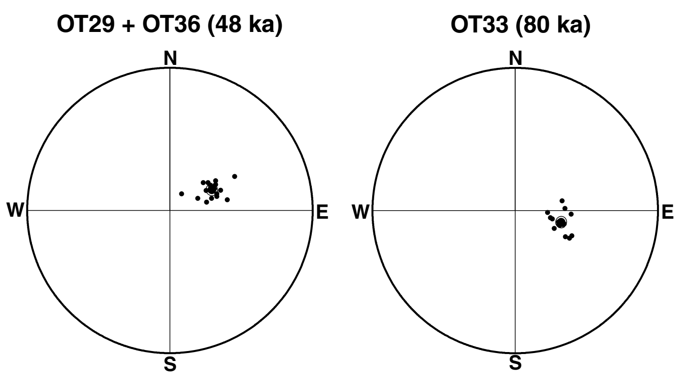

Fig. 4. Equal area plots of sample directions for the 48 ka and 80 ka lavas which indicate existence of two excursions in Japan in the latest Pleistocene. The site mean direction is shown by a larger symbol with a circle of 95% confidence.

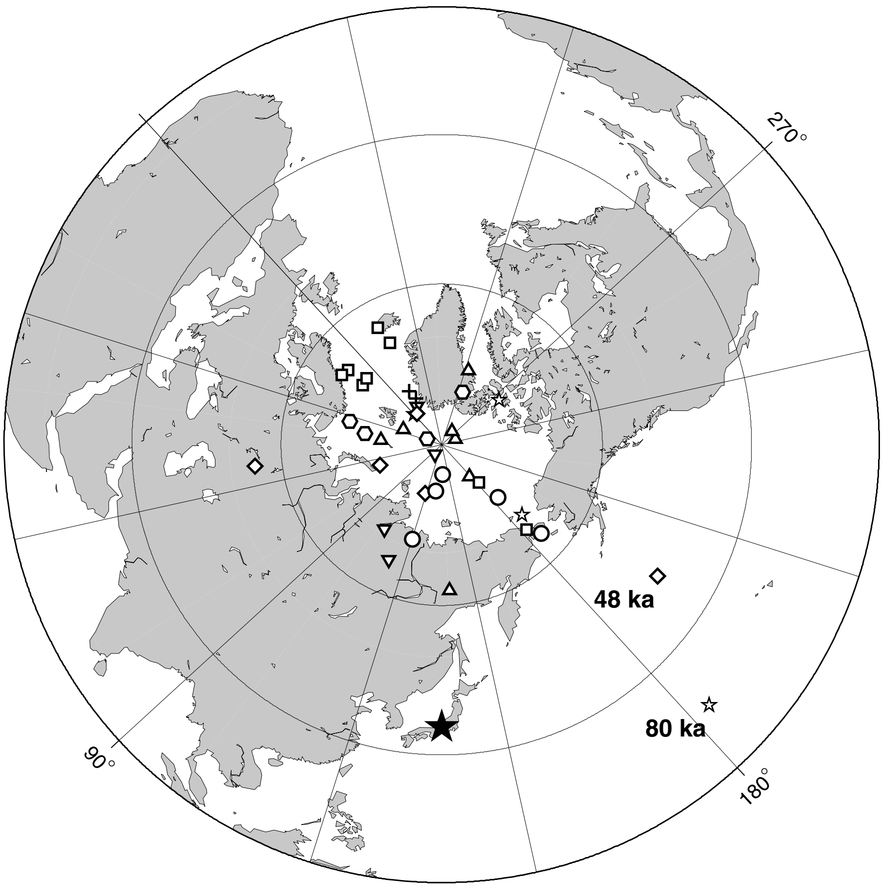

Fig. 5. Equal area plot of VGPs from all sites with different symbols for each age group. Cross, Sannoike Volcano (21±5 ka); circle, Ichinoike Volcano (29±5 ka); hexagonal, Yonnoike Volcano (36±3 ka); diamond, Mamakodake Volcano (48±4 ka); square, Kusakidani Volcano (58±11 ka); triangle, Okunoin Volcano (59±7 ka); inverted triangle, Kongodo Volcano (66±5 ka); star, four lavas for 80–84 ka. Large closed star indicates the site location. Note two low latitude VGPs which are excursions at 48 ka and 80 ka.

tion of the 80 ka lava should also be certain because two outcrops which are 20 m apart across a gully gave the same results. These intermediate directions are characterized by easterly deflected declination, and their implications will be discussed later. Site mean directions with Fisher statistics (Fisher, 1953) are summarized in Table 1 for total of 40 sites remained and an equal area plot of VGPs is shown in Fig. 5.

Taking advantage of accurate ages assigned to each lava group, it is worth examining whether any long term temporal change could be recognized in the paleodirections shown in Fig. 5. There are some groupings of the VGP position according to the age group; five VGPs from Ichinoike Volcano (29 ka, open circle) locate at the Pacific side from the north pole while four VGPs from Yonnoike Volcano (36 ka, open hexagonal) come to the Atlantic side. However, this is probably not significant because of too small sample number for each group. In fact, two of eight VGPs from Kusakidani Volcano (58 ka, open square) are much different in their position from the rest. Hence, the different VGP positions from lava groups of different age merely indicates rather short time span covered by the lava group. Nevertheless, taking altogether, the data constitute a set of VGPs which are scattered fairly evenly around the north pole as seen in Fig. 5.

Three lava groups taken at the summit are from lava successions of 5 to 8 flows. There are some suggestions from combined studies of paleomagnetism and radiometric dating that lava successions are often formed in a short time span (ex., Mankinen *et al.*, 1986). Taking this fact in mind, paleomagnetic results with similar directions are combined when the data come from the same volcano (not necessarily from a lava succession). Statistical test by McFadden and Lowes (1981) was used with a level of significance of 5%. There are only two cases in which combining site mean directions was necessary; four successive lava flows from Kusakidani Volcano (58 ka) and two lava flows of proximity of site location from Sannoike Volcano (21 ka). Data was combined from the beginning for the two intermediate directions (OT29, OT36) because they are from the same flow.

After merging some of the individual data, there remained 35 paleodirections including two possible excursions. When these two excursions are excluded, the mean VGP and the mean field direction are (86.8°N, 78.5°E) with A_{95}=5.0° and (I=55.5°, D=356.0°) with α_{95}=4.3°, respectively. On the other hand, the ASD for VGP was 15.6° with lower and upper confidence limits by Cox (1969, 1977) of 13.3° and 18.9°, respectively. These values are after correction of the mean within-site dispersion of 7.5° for the mean sample number of 6.9. The obtained ASD values are consistent with the typical values for the last 5 my (McElhinny and McFadden, 1997).

The two paleodirections which were excluded from estimation of ASD are considered to represent excursions be-

Table 1. Site mean paleodirections from the Younger Ontake Volcano.

Site	Lat (°N)	Lon (°E)	Inc	Dec	α_{95}	N	Plat (°N)	Plon (°E)	$\bar{J}$ (A/m)	s_J (A/m)	Remark
— Sannoike Volcano, 21±5 ka —											
OT44	35.905	137.491	44.1	353.3	1.6	6	78.4	349.0	1.3	0.3	
OT45	35.904	137.489	45.8	354.6	2.3	6	80.2	346.8	1.1	0.4	
OT44+OT45			44.9	353.9	1.3	12	79.2	348.1			†
— Ichinoike Volcano, 29±5 ka (lava succession except OT46) —											
OT07	35.892	137.479	60.7	44.4	34.9	8	—	—	76	49	‡, ∗
OT05	35.893	137.483	63.0	358.5	4.7	6	81.4	130.3	3.3	2.0	
OT04	35.893	137.483	69.4	351.2	2.8	8	71.7	120.4	3.0	0.8	
OT02	35.893	137.483	66.7	28.7	12.2	6	65.2	185.9	2.5	0.2	
OT03	35.893	137.483	60.4	0.2	4.1	9	84.5	139.1	4.2	1.9	
OT46	35.900	137.492	63.2	14.6	2.3	6	75.8	184.6	3.6	1.5	
— Yonnoike Volcano, 36±3 ka —											
OT28	35.918	137.460	52.0	343.0	2.3	7	75.6	39.1	2.0	0.2	
OT41	35.910	137.486	49.0	340.2	3.6	6	72.4	33.2	4.9	2.2	
OT42	35.910	137.486	54.2	356.7	5.0	6	87.1	24.8	2.9	2.7	
OT43	35.910	137.486	44.5	4.3	2.9	6	79.6	295.6	1.9	0.4	
— Mamakodake Volcano, 48±4 ka —											
OT29	35.937	137.464	65.0	63.4	4.6	12	42.6	193.4	5.3	7.1	
OT36	35.936	137.464	60.0	64.4	4.1	6	40.4	201.1	13	24	(1)
OT29+OT36			63.3	63.8	3.3	18	41.9	196.2			†
OT31	35.952	137.509	49.2	354.7	2.9	7	82.6	356.1	3.3	1.3	
OT35	35.950	137.462	58.2	345.4	1.1	6	78.0	66.0	1.2	0.3	
OT39	35.922	137.550	63.3	355.7	3.8	6	80.5	118.7	2.2	0.2	
OT40	35.988	137.531	51.6	317.4	4.3	6	54.8	54.1	7.9	2.1	
— Kusakidani Volcano, 58±11 ka (lava succession) —											
OT15	35.901	137.480	66.8	24.4	5.3	7	67.7	182.6	29	19	
OT16	35.901	137.480	61.4	9.4	5.3	7	80.2	182.3	40	43	‡
OT17	35.901	137.480	37.0	341.6	4.3	7	67.8	9.0	2.1	0.4	
OT18	35.901	137.480	37.9	340.2	2.7	7	67.4	12.6	8.6	8.0	
OT19	35.901	137.480	41.4	344.1	2.5	8	71.7	10.4	13	19	‡
OT20	35.901	137.480	39.8	345.0	4.6	8	71.4	6.0	2.6	1.5	
OT17-OT20			39.0	342.7	3.0	4	69.5	9.5			†
OT22	35.902	137.485	25.7	348.0	8.5	7	65.2	346.2	37	48	‡
OT21	35.902	137.485	30.7	350.2	2.8	8	68.8	344.3	1.7	0.2	
— Okunoin Volcano, 59±7 ka (lava succession) —											
OT14	35.883	137.483	53.7	346.3	3.5	7	78.7	43.1	9.1	3.4	
OT13	35.883	137.483	75.7	3.1	4.9	8	62.8	140.6	15	17	‡
OT12	35.883	137.483	52.2	351.6	13.6	8	82.4	26.0	19	17	‡
OT11	35.883	137.483	54.3	3.1	4.3	6	87.3	249.2	6.4	2.3	
OT10	35.883	137.483	60.6	6.9	2.7	7	82.2	178.7	8.7	5.4	
OT09	35.883	137.483	52.8	2.3	4.4	8	86.9	279.8	4.7	3.3	
OT08	35.883	137.483	39.0	5.3	12.7	8	75.4	297.6	2.4	2.5	
— Kongodo Volcano, 66±5 ka —											
OT24	35.874	137.554	57.0	358.4	1.4	7	87.8	101.3	2.6	0.6	
OT26	35.894	137.525	83.1	294.3	22.9	7	—	—	50	36	‡, ∗
OT37	35.898	137.525	71.5	342.5	5.0	6	66.5	112.7	4.2	1.2	(2)
OT38	35.899	137.533	67.6	343.4	7.3	6	71.1	103.4	2.4	0.8	
OT47	35.900	137.492	47.7	354.8	2.5	6	81.6	350.6	3.5	0.5	
— Nigorigo Volcano, 80±4 ka —											
OT33	35.930	137.447	63.0	104.2	3.2	16	15.9	183.3	1.1	0.4	
OT34	35.920	137.454	49.3	354.1	3.8	6	82.4	359.8	3.1	0.6	
— Miureyama Lava, 84±4 ka —											
OT06	35.889	137.468	45.5	11.9	5.5	7	76.5	265.5	0.8	0.1	
— Yunotani Lava, 84±5 ka —											
OT27	35.907	137.462	65.0	21.9	4.7	8	70.3	186.4	1.4	0.3	

Note:
Lat, Lon, latitude and longitude of site locality; Inc, Dec, site mean direction; α_{95}, 95% confidence circle for the mean direction; N, number of specimens used for the site statistics; Plat, Plon, latitude and longitude of VGP; $\bar{J}$, s_J, mean and standard deviation of NRM intensity.
Remark:
∗, rejected due to a large α_{95}; †, combined results; ‡, site mean direction was calculated by the great circle method; (1), the same lava as OT29; (2) possibly the same lava as OT26.

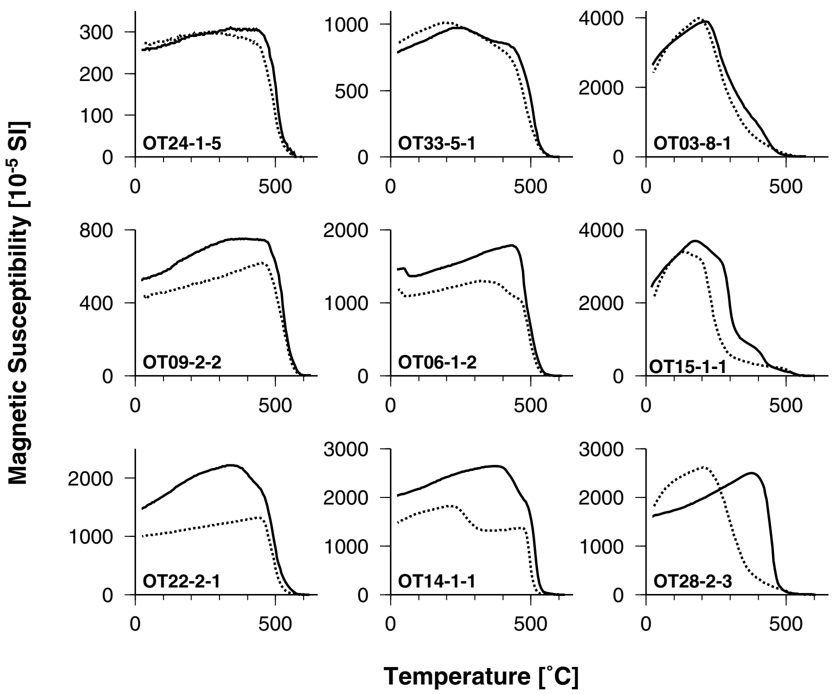

Fig. 6. Representative χ-T curves in which solid and dotted lines indicate heating and cooling runs, respectively. χ-T curves were grouped to three ranks of A (top row), B (middle row), and C (bottom row) according to the repeatability of the heating and cooling runs.

cause of their VGP positions being lower than 45°N. One from the 48 ka lava is characterized by slightly deep inclination of 63° and by easterly deflected declination of 64°. Another one from the 80 ka lava is characterized by similar inclination of 63° and further easterly deflected declination of 104°. These paleodirections are not much conspicuous with VGP positions which does not go beyond the equator. Nevertheless, identification of these excursions from volcanic rocks is important because they are possibly related to some of the excursions reported for the latest Pleistocene as will be discussed later.

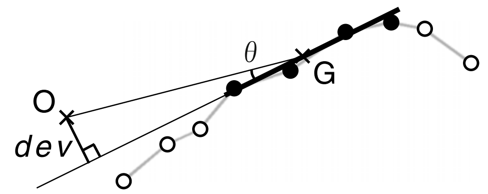

Fig. 7. Two parameters used to judge criterion 4) less ambiguously. The figure represents end points of remanence vectors for zero-field steps, where closed and open circles indicate selected and rejected steps, respectively. Principal component is shown by a thick line and G is its center of mass where O is the origin. Actual dev used is normalized by the NRM intensity.

4. Preliminary Paleointensities

Paleointensity experiments were made to 36 samples from 6 sites using the Coe's methodology (Coe, 1967) of the Thellier's method (Thellier and Thellier, 1959). Samples were selected based on the stability of remanence to both AF and thermal demagnetizations and the smallness of secondary component. Repeatability of magnetic susceptibility versus temperature (χ-T) curve between heating and cooling runs was also taken into consideration to the sample selection. The χ-T curves were grouped to three ranks (A, B, and C) according to the repeatability of heating and cooling runs. Representative χ-T curves are shown in Fig. 6 in which three examples from each category are placed from top (class A) to bottom (class C) rows. Only four lavas were grouped to class A, so samples from group B were also used for the paleointensity experiments. Two series of the paleointensity experiments were made first in air and second in vacuum of $\sim$1 Pa, making it possible to experiment in different atmosphere for the same lava.

Results were analyzed on the NRM-TRM diagram or Arai plot (Nagata *et al.*, 1963). Acceptance criteria used in this study are 1) at least four data points are included in the linear segment, 2) correlation coefficient of the segment should be larger than 0.98, 3) no indication of VRM in the orthogonal plot of zero field steps which correspond to the linear segment, 4) similarly no indication of TCRM judged by that the corresponding zero field steps decrease toward the origin of the orthogonal plot, 5) pTRM test within the linear segment gives a positive result of less than 5% of the total TRM which is defined as the extrapolated TRM on the Arai plot, and 6) room temperature magnetic susceptibility should remain within 20% of the original value for the temperature range of the linear segment.

To judge the criterion 4) less ambiguously, two parameters were introduced; difference angle (θ) and deviation (dev) described in Fig. 7. θ is the difference angle between the principal component corresponding to the selected linear segment (thick line) and the direction of their center of mass (G). dev is the minimum distance of the extension of the principal component from the origin, divided by the NRM intensity which is defined as the extrapolated NRM on the Arai plot.

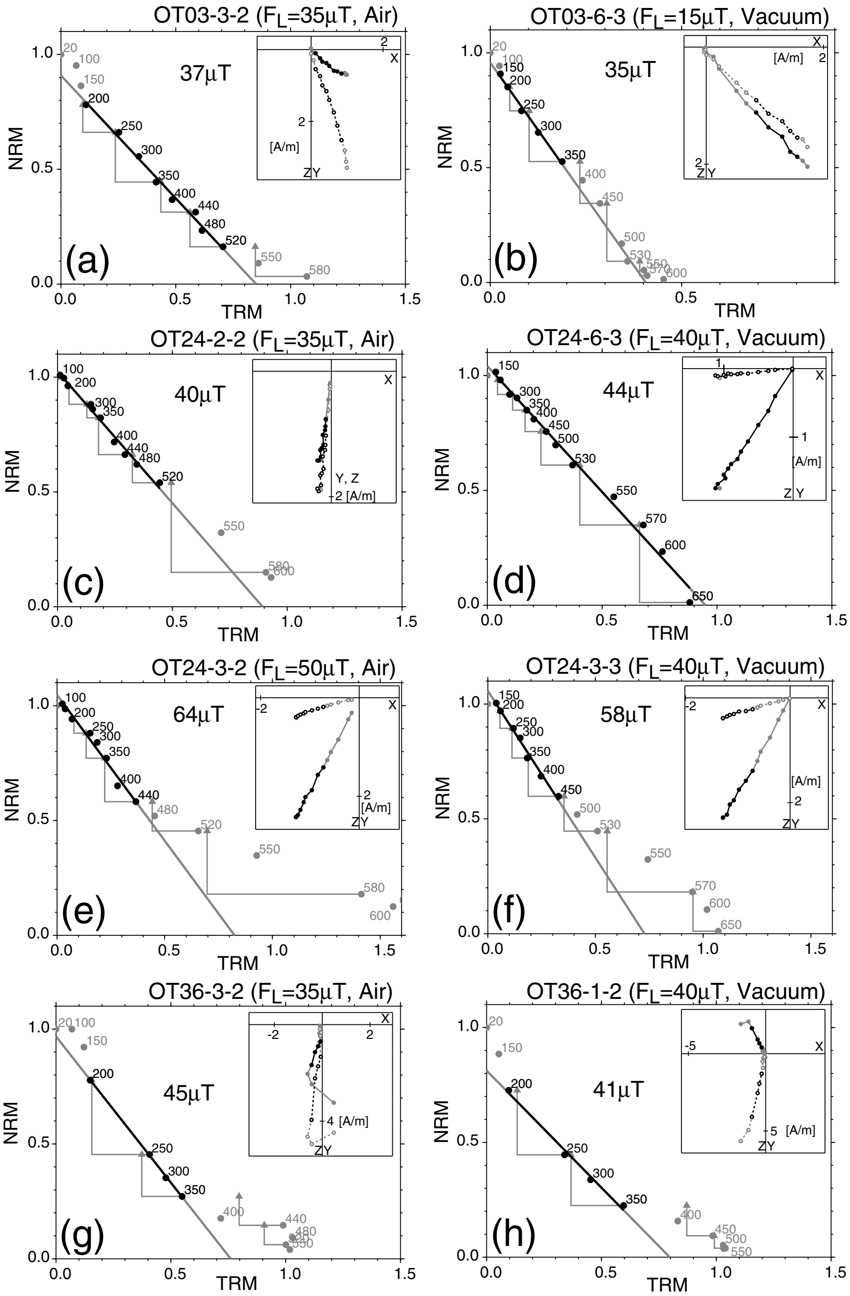

Fig. 8. Examples of successful Arai plot in the Thellier's paleointensity experiment. Inset in each figure shows an orthogonal plot of NRM steps in sample coordinate. The laboratory field was applied to the positive x-axis for the experiments in air, and the positive z-axis for those in vacuum. All data points excluded from the linear segment are shown by dimmed symbols. In the Arai plot, pTRM tests are shown in a dimmed triangle for all steps. Closed and open circles in the orthogonal plot are projections on the X-Y and X-Z planes, respectively.

These parameters have no statistical background and obviously depend on the difference angle between the directions of NRM and the inducing field. Nevertheless they were useful to judge the results less subjectively, and θ and dev of less than 10° and 10%, respectively, were adopted as acceptance criteria. Calculation of the slope of the Arai plot and other quality factors was made following Coe *et al.* (1978) and the principal component on the orthogonal plot was determined by the method of Kirschvink (1980).

Representative successful Arai plots are shown in Fig. 8. Each diagram includes an inset which shows an orthogonal plot of zero field steps in sample coordinate. The laboratory field was applied to the positive x-axis for the experiments in air, and the positive z-axis for those in vacuum. Two results shown in Fig. 8(a) and (b) were obtained from the same lava (OT03) in different experimental conditions of furnace atmosphere and laboratory field. Although the small laboratory field of 15 μT used for OT03-6-3 was originally aimed to experiment on the samples from the lavas of an intermediate paleodirection, good consistency of the result with other OT03 samples shows reliability of the experiments.

Figure 8(c) and (d) show another case of consistent results of about 40 μT obtained from the same lava (OT24). This flow is a rhyolite lava which is rare in the Ontake Volcano, but appearance of data points on the Arai plots was not different from those of andesite lavas. Both of two results ob-

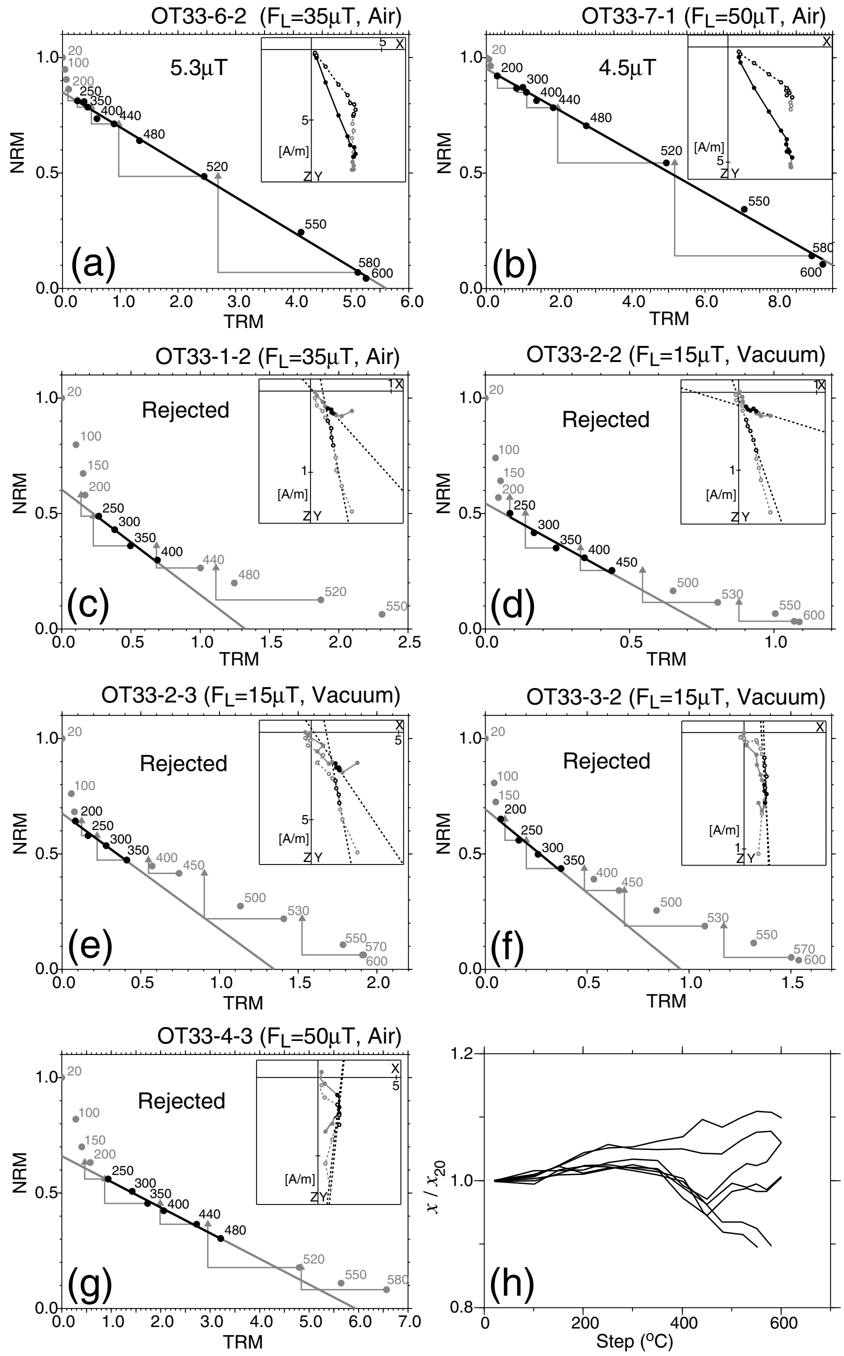

Fig. 9. All Arai plots from the lava flow of the 80 ka excursion. Symbols are the same as those used in Fig. 8. Only two samples out of seven were successful, giving very low paleointensities of about 5 μT. Normalized χ-step curves are shown for all samples in (h), where the successful two samples correspond to the uppermost two curves which lack in abrupt change of χ at about 400°C.

tained in different atmosphere were successful, although the result is better in vacuum than in air. However, much larger paleointensity of about 60 μT was obtained from the same lava as shown in Fig. 8(e) and (f). These results were obtained from two specimens of the same core (OT24-3) which were experimented in different atmosphere with a slightly different laboratory field. There is no reason to reject these high values as all acceptance criteria are satisfied and the two results from the same core are consistent. This puzzling result is similar to the case of Hawaii 1960 lava (Tanaka and Kono, 1991) in which one sample gave much higher value than others. Possible interpretation of such inconsistency in the Thellier's experiment would be effect of TCRM which was formed during the original cooling of the lava at the site (Abokhodair, 1977; Yamamoto *et al.*, 2003). In the case of OT24, however, it is difficult to conclude which of the results is an outlier because distinctive samples involved in the experiment were only three although six specimens were used. Hence, all successful results were used to obtain the site mean paleointensity.

Results from the 48 ka lava with an intermediate paleodirection are shown in Fig. 8(g) and (h). No particularly small or large paleointensity was obtained for this intermediate paleodirection.

Table 2. Sample results of paleointensity experiment.

Specimen	T_1 (°C)	T_2 (°C)	n	$-$r	$-$b	σ_b	θ (°)	dev (%)	f	g	q	F_L (μT)	F $\pm$ ΔF (μT)	Atmosphere
OT03-3-2	200	520	8	0.995	1.069	0.043	1.6	1.3	0.68	0.85	14.2	35	37.4 ± 1.5	A
OT03-6-3	150	350	5	0.996	2.355	0.117	3.4	4.6	0.40	0.73	5.9	15	35.3 ± 1.7	V
OT03-7-2	250	530	7	0.993	0.726	0.039	5.9	5.2	0.65	0.83	10.0	40	29.0 ± 1.5	V
Mean of OT03 (29±5 ka): F = 33.9 ± 4.4 μT (N=3, n/n0=3/5), VDM = (5.77 ± 0.74)×10^{22} Am^2														
OT36-1-2	200	350	4	0.996	1.019	0.067	3.9	3.6	0.62	0.59	5.6	40	40.8 ± 2.7	V
OT36-2-2	200	350	4	0.991	1.080	0.103	3.2	3.3	0.59	0.63	4.0	40	43.2 ± 4.1	V
OT36-3-2	200	350	4	1.000	1.273	0.022	5.8	4.9	0.52	0.53	15.7	35	44.6 ± 0.8	A
OT36-3-3	200	350	4	0.995	0.952	0.066	3.7	3.3	0.50	0.60	4.2	40	38.1 ± 2.7	V
Sample mean of OT36-3													41.3 ± 4.6	
OT36-4-3	200	400	5	0.994	0.728	0.047	3.7	3.4	0.50	0.74	5.7	50	36.4 ± 2.3	A
Mean of OT36 (48±4 ka): F = 40.4 ± 2.9 μT (N=4, n/n0=5/6), VDM = (6.62 ± 0.47)×10^{22} Am^2														
No results from OT17 (58±11 ka): n/n0 = 0/5														
OT24-2-2	100	520	10	0.994	1.148	0.045	1.9	2.7	0.46	0.85	10.0	35	40.2 ± 1.6	A
OT24-2-3	250	530	7	0.995	2.483	0.114	0.5	0.6	0.44	0.82	7.8	15	37.2 ± 1.7	V
Sample mean of OT24-2													38.7 ± 2.1	
OT24-3-2	100	440	8	0.988	1.271	0.081	2.3	3.2	0.41	0.82	5.3	50	63.6 ± 4.0	A
OT24-3-3	150	450	7	0.994	1.454	0.069	2.6	3.6	0.38	0.82	6.6	40	58.2 ± 2.8	V
Sample mean of OT24-3													60.9 ± 3.8	
OT24-6-2	20	600	14	0.998	0.811	0.017	0.7	1.0	0.76	0.84	31.5	50	40.6 ± 0.8	A
OT24-6-3	150	650	13	0.996	1.096	0.031	0.7	0.7	0.96	0.88	30.1	40	43.9 ± 1.2	V
Sample mean of OT24-6													42.2 ± 2.3	
Mean of OT24 (66±5 ka): F = 47.3 ± 11.9 μT (N=3, n/n0=6/9), VDM = (8.40 ± 2.12)×10^{22} Am^2														
OT37-1-2	200	400	5	0.998	0.725	0.024	8.7	9.1	0.56	0.71	11.9	35	25.4 ± 0.8	A
Single result from OT37 (66±5 ka): F = 25.4 μT (N=1, n/n0=1/4), VDM = 3.75×10^{22} Am^2														
OT33-6-2	250	600	10	0.999	0.152	0.002	1.3	1.5	0.91	0.79	48.8	35	5.3 ± 0.1	A
OT33-7-1	200	600	11	0.999	0.090	0.002	2.8	3.2	0.86	0.82	38.4	50	4.5 ± 0.1	A
Mean of OT33 (80±4 ka): F = 4.9 ± 0.6 μT (N=2, n/n0=2/7), VDM = (0.80 ± 0.10)×10^{22} Am^2														

Note: T_1, T_2, lower and upper temperatures for the linear segment; n, number of data point included in the linear regression; r, correlation coefficient of the linear segment; b, slope of the segment; σ_b, standard error of b; θ, dev, difference angle and deviation of the selected NRM component from the origin on the orthogonal plot; f, g, q, quality parameters after Coe *et al.* (1978); F_L, laboratory field strength; F, ΔF, paleointensity and its standard error; Atmosphere, air (A) or vacuum (V).
Site mean is a simple average of the sample paleointensities, and is shown in italic with its standard deviation.
N, number of samples involved in the site mean; n, n0, number of specimens accepted and used.

Figure 9 shows all results from another lava with intermediate direction of 80 ka. Experiment was successful in only two samples out of seven, giving very small paleointensities of about 5 μT. The two successful Arai plots are shown in Fig. 9(a) and (b) in which all the acceptance criteria were satisfied. These two results were obtained from the first series of the experiments which was made in air. Unfortunately the experiment was unsuccessful in the second series made in vacuum with a reduced inducing field of 15 μT as shown in Fig. 9(d), (e), and (f).

In most unsuccessful samples there was a linear segment in which pTRM test was positive except OT33-2-2 (d) which failed over the whole temperature range. Hence, as known from the orthogonal diagram, the main reason to reject the results was criterion 4) which states no indication of TCRM in the direction of zero-field steps.

Figure 9(h) shows curves of χ versus temperature step for all samples. This figure simply illustrates that there was no drastic change of χ for all the samples. Interesting fact, however, is that the χ-step curves for the successful two samples correspond to the uppermost two curves which show gradual increase of χ with temperature. Five unsuccessful samples, on the other hand, show a rather abrupt decrease of χ around the step of 400°C. Possible connection of the kinked χ-step curves to the failure of the Thellier's experiment was also recognized in the Hawaii lavas by Tanaka and Kono (1991).

Details of the sample results of the paleointensity experiments are summarized in Table 2 in which the site mean is a simple average without any weighting.

5. Discussion

The ASD of 15.6° for VGP obtained in this study represents a relatively short time span which is accurately confined between about 20 and 90 ka. Nevertheless, the obtained ASD is not different from a typical value for the last 5 my. By analyzing the PSV for the last 10 ky, Ohno and Hamano (1993) suggested that a large value of ASD reflects low dipole moment because the level of non-dipole field stayed almost constant during the term they studied. In the past studies, broad paleointensity low was suggested for 20–50 ka (McElhinny and Senanayake, 1982; Tanaka *et al.*, 1994). This suggestion is still correct but accumulation of

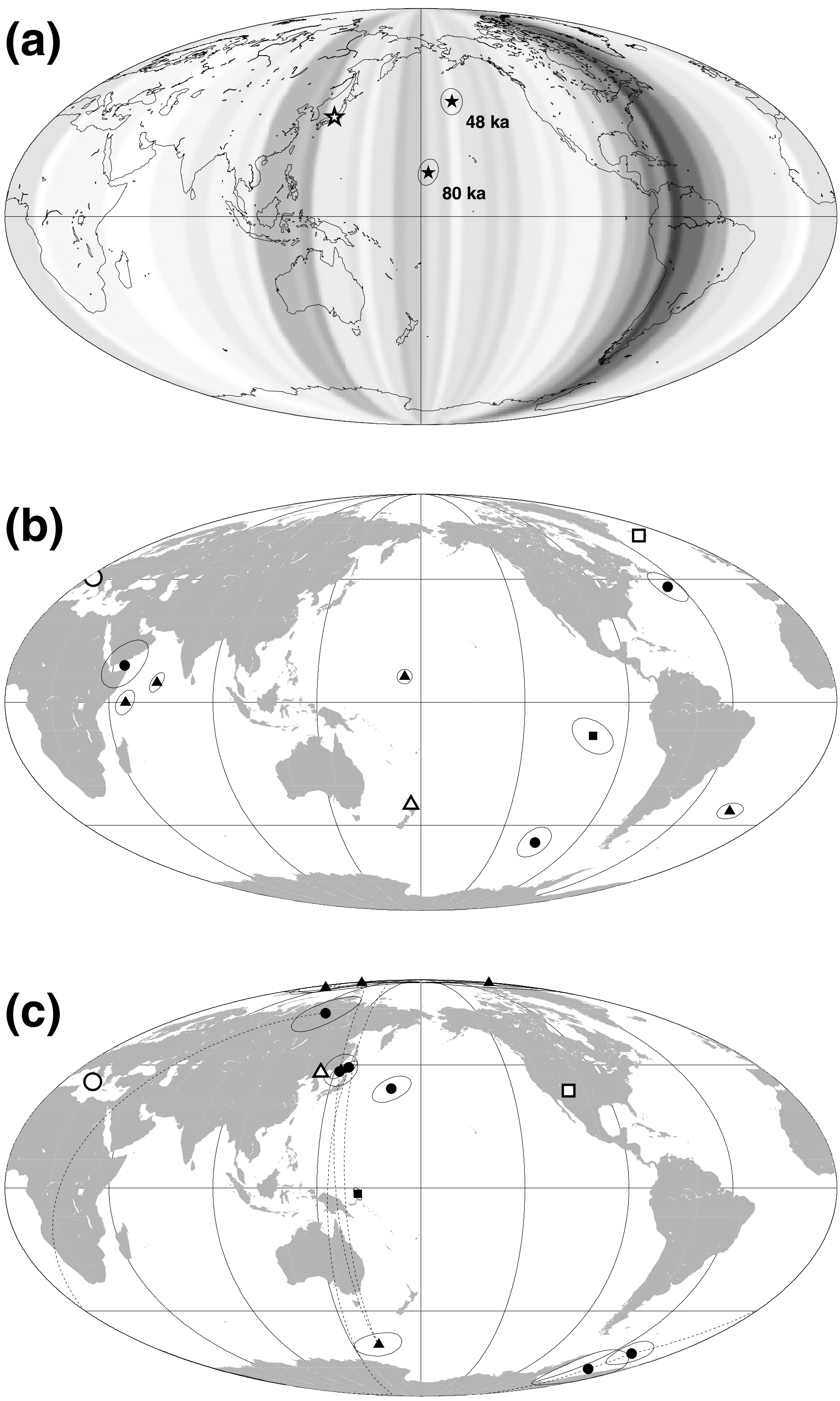

Fig. 10. Plot of VGPs from the 48 ka and 80 ka excursions in this study (a), and those previously reported from lavas for the Laschamp excursion (b) and the Blake excursion (c). VGPs from different sites are shown by different symbols, where larger open ones indicate the site locations. In (b), the VGP positions are overall means except for three sites from New Zealand which are lava means. In (c), all VGPs are lava means and fine dotted lines indicate stratigraphic relations among them. In (a), relative darkness of gray shade shows relative occurrence of the equatorial crossings of the transitional VGP paths from sediments for the last 12 my compiled by Laj *et al.* (1992). The plots were drawn by the Mollweide projection.

data from volcanic rocks shows quite oscillatory nature of paleointensity in the time range of 40–100 ka, and recent review was given by Laj *et al.* (2002) with many new data from a Hawaii drilled core. Hence the value of ASD from this study for the time span of 20–90 ka which is also typical for the last 5 my is not surprising. Relative paleointensities from sediments also show oscillatory curves for the last 100 ky although the details of fluctuation are not necessarily consistent with volcanic records (Guyodo and Valet, 1996; Laj *et al.*, 2000). Actually, the preliminary paleointensities obtained in this study, VDM of $3.8–8.4\times10^{22}$ Am^2, are not necessarily low except for the excursion from the 80 ka lava.

The two intermediate paleodirections found from the 48 ka and 80 ka lavas are characterized by easterly deflected declination. These two excursions give VGP positions of (41.9°N, 196.2°E) and (15.9°N, 183.3°E), and VDMs of 6.7 and 0.8 ($\times 10^{22}$Am^2) for the former and latter, respectively. Low VGP latitude and small paleointensity obtained from the 80 ka lava is typical for an excursion, while the 48 ka lava is not so conspicuous in paleointensity. Possible excursion from the Ontake Volcano was suggested in the past by Hirooka *et al.* (1978) from some of the tephra layers. This was also found from ash and loam layers originated from the Yatsugatake Volcano which is 80 km apart from the Ontake Volcano (Aida, 1978). Comparison of these two studies with our new results was avoided, because consistency of the data from two sections were low in Hirooka *et al.* (1978) and no magnetic cleaning was involved in Aida (1978). Nevertheless, the general paleodirections of the previous results are similar to ours characterized by easterly deflected declination.

In the review of excursions in the Brunhes chron by Langereis *et al.* (1997), doubt was shed to the occurrence of excursions from the Lake Biwa, Japan, which were found from 197 m core drilled in 1972 (Kawai *et al.*, 1972; Nakajima *et al.*, 1973; Yaskawa *et al.*, 1973). Main reason of the negative suggestion to the Lake Biwa excursions is the fact that no excursion was found in the new core of 1422.5 m length which was drilled near the original site 10 years later (Torii *et al.*, 1983). However, based on updated chronology by Machida *et al.* (1991), Hyodo and Minemoto (1996) concluded high possibility of occurrence of Lake Biwa excursions by reexamining the old record of the 200 m Lake Biwa which has some signatures similar to those in marine sediments by Ohno *et al.* (1993). Further scientific drilling will be necessary to reconcile the possibility of the Lake Biwa excursions.

Although there have been some other indications of excursions for the latest Pleistocene from Japan such as a possible Blake excursion by Manabe (1977) from northeast Japan[1], all the reports are not conclusive. Hence, finding of intermediate directions from Ontake lavas gives a strong evidence that some of the excursions in the latest Pleistocene reported worldwide were also observed in Japan.

Correlating the two excursions reported in this study to those previously reported worldwide is not necessarily an easy task. Although the K-Ar ages associated with the Ontake lavas are very accurate, there is no stratigraphic confinement from the global age markers such as δ^{18}O curves. Statistical error attached to a radiometric age is usually much smaller than the true error. Error of 15% was suggested by Matsumoto *et al.* (1989) when an ideal basalt of 0.05 Ma is dated by peak comparison method of K-Ar dating. Considering also a small inconsistency between the stratigraphy and K-Ar ages as shown in Fig. 1 (corrected from the original figure as mentioned in Section 2), a realistic error of the ages would be about 10–15 ky. Hence, the excursion of the 48 ka lava is probably correlated to the Laschamp excursion (Bonhommet and Zähringer, 1969). On the other hand, the excursion of the 80 ka lava is too young to be correlated to the Blake excursion (Smith and Foster, 1969). Recent studies by marine sediments which incorporate δ^{18}O measurements confine the age and duration of the Blake excursion quite accurately as 110–120 ka (ex., Tucholka *et al.*, 1987; Fang *et al.*, 1997). Hence it is incorrect to correlate the 80 ka lava excursion to the Blake excursion. Possible candidates of excursion are the one found from sediments of Norwegian-Greenland Sea and Arctic Ocean, which are stratigraphically between the Laschamp and the Blake excursions (Bleil and Gard, 1989; Nowaczyk *et al.*, 1994). This excursion might also be recorded in the 1 km core of Hawaii lavas by Holt *et al.* (1996), because, if the inclination record is carefully examined, anomalously low inclination (No. 32) is recognized between the lavas which correspond to the Laschamp and the Blake excursions.

In the studies of the Blake excursion from lava successions at Island of Lipari, Italy (Zanella and Laurenzi, 1998) and at Jilin, northeastern China (Zhu *et al.*, 2000), it was pointed out that VGP positions came to one of the preferred longitudinal bands of the transitional paths found from sediments (Laj *et al.*, 1991). VGP positions of the 48 ka and 80 ka excursions from this study are rather in the central Pacific region as shown in Fig. 10(a) in which closed and open stars indicate the VGP position and the site location, respectively. In the figure, relative darkness of gray shade shows relative occurrence of the equatorial crossings of the transitional VGP paths for the last 12 my based on the compilation by Laj *et al.* (1992).

Figure 10(b) shows VGPs from the Laschamp volcanic sites at Shaine des Puys, France (circle), Skalamaelifell, Iceland (square), and Auckland volcanic field, New Zealand (triangle), where open symbols indicate the site location (Roperch *et al.*, 1988; Chauvin *et al.*, 1989; Levi *et al.*, 1990; Shibuya *et al.*, 1992). The VGP positions are overall means except for three sites from New Zealand which are lava means. VGPs from France and Iceland come to the region along north and south America except the one from France which is at the eastern edge of Africa. One site from New Zealand lavas also gave a VGP near South America, and other two sites gave VGPs near eastern Africa which are very close to the one found from France. Most of the anomalous paleodirections from New Zealand gave VGPs at the central Pacific region (in the figure, only the grand mean position is shown), similar to those from the 48 ka and 80 ka lavas in this study.

Figure 10(c) shows the Blake excursion VGPs from lavas at Italy (circle) and China (triangle) which come to the western Pacific region as mentioned before. In the figure, all VGPs are lava means and fine dotted lines indicate stratigraphic relations among them. One VGP shown by a square is the one from 128 ka Laguna basalt, New Mexico, U.S.A. (Champion *et al.*, 1988), which also comes to the western Pacific region.

Similar VGP positions were sometimes observed during excursion from different sites which are far apart on the globe. For the Laschamp excursion, similar VGP positions near the eastern Africa were observed at France and New Zealand as shown in Fig. 10(b). Almost identical VGP po-

1) Another report from the northeast Japan by Tanaka and Tachibana (*J. Geomag. Geoelectr.*, **33**, 287–292, 1981) was an error as stated at p. 99 of Jacobs (1984). Correlating the welded tuff layer to a sand and gravel bed which was dated at 22 ka by ^{14}C method was a simple mistake. Since then, K-Ar ages of 0.9–1.2 Ma (Suto, 1982; Tamanyu and Lanphere, 1983) and a fission track age of 716 ka (Machida *et al.*, 1987) were reported for this welded tuff.

sitions near Japan Island were found from Italy and China during the Blake excursion, although it is difficult to see in Fig. 10(c) due to overlapped symbols. Proximity of the transitional VGPs during excursion indicates a dipole structure of the transitional field. This can be attained by disappearance of the axial dipole field and dominance of the equatorial dipole. Preferred direction of the equatorial dipole is probably related to some kind of features in the core-mantle boundary. The preferred directions seem to include not only the two longitudinal bands of the preferred transitional VGP paths from sediments but also the central Pacific region as found from the Auckland volcanic field, New Zealand and the Ontake Volcano, Japan in this study.

6. Conclusion

Angular dispersion obtained from the Younger Ontake Volcano for the accurately confined period of 20–90 ka is not much different from the typical value for the last 5 my. In view of the variable feature of paleointensity in the period of 40–100 ka which precedes the global low of 20–40 ka, the obtained typical value of ASD is not surprising. Preliminary paleointensities of 25–47 μT obtained in this study from three lavas with ordinary paleodirection are consistent with this. Two low latitude VGPs found from 48 ka and 80 ka andesite lava flows indicate existence of two excursions in Japan during the latest Pleistocene. VGP latitude of the 48 ka excursion is moderately low of 42°N and is not accompanied by a low paleointensity, while the VGP latitude and the preliminary paleointensity are 16°N and about 5 μT, respectively, for the 80 ka one. The two excursions found in this study support previous studies of excursion in Japan even though most of them were not conclusive. It is natural to suppose that the 48 ka excursion corresponds to the Laschamp excursion. The 80 ka excursion, on the other hand, is too young to correlate to the Blake excursion even though a realistic error of about 10–15 ky is allowed to the K-Ar age of the lava. Possible candidate to correlate this excursion is the one from sediments of Norwegian-Greenland Sea and Arctic Ocean, which are stratigraphically between the Laschamp and the Blake excursions. Both VGPs from the 48 ka and 80 ka lavas come to the central Pacific region, which is fairly apart from the two preferred bands of the transitional VGP paths from sediments. They are rather close to one of the VGP groups for the Laschamp excursion found from New Zealand lavas.

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