RADIOCARBON DATING OF FUGENDAKE VOLCANO IN UNZEN, SW JAPAN

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ABSTRACT. This article presents new radiocarbon ages for the lavas, pyroclastic flow, and lahar deposits that originated from the Fugendake and Mayuyama volcanoes of the Younger Unzen Volcano, SW Japan. Nine charcoal samples were collected from the lavas and pyroclastic flow deposits, and 17 soil samples from the underlying volcanic-related products. This data set, together with previously published ages (thermoluminescence, K-Ar, fission track, and ¹⁴C), yielded new information about the timing of Late Pleistocene eruptions and an improved understanding of the evolution of the Fugendake and Mayuyama volcanoes. Fugendake Volcano started to build within the scar of Myokendake around 29 cal ka BP, and its eruption products spread over the flank of Myokendake. The remarkable eruptions of Fugendake Volcano included the lava and pyroclastic flow deposits around 22, 17, 12, and 4.5 cal ka BP. Subsequent historical eruptions occurred in AD 1663, 1792, and 1991–1995. Developed on the eastern extension of Fugendake Volcano, Mayuyama Volcano was active during the building stage of Fugendake at 4.5 cal ka BP. This study also identified a pumice eruption at ~10 ka and 2 volcanic-related lahar deposits around 1.6 and 0.7 ka, which need to be addressed in future research.

INTRODUCTION

Unzen Volcano is situated in an active graben, approximately 70 km west of the volcanic front of SW Japan (Figure 1). It began ~500 ka ago, and the latest eruption occurred in 1991–1995. The composite volcanic edifice can be subdivided into the Older (500–150 ka) and Younger Unzen volcanoes (150–0 ka). The latter comprises the Nodake, Myokendake, Fugendake, and Mayuyama volcanoes (Watanabe and Hoshizumi 1995; Hoshizumi et al. 1999). Geological observation suggested that Fugendake Volcano was built within the horseshoe-shaped scar of Myokendake, and its eruption products spread over the flank of Myokendake (Figure 2). Nodake is an isolated volcanic center adjacent to Myokendake. Mayuyama is completely isolated from these 3 volcanoes.

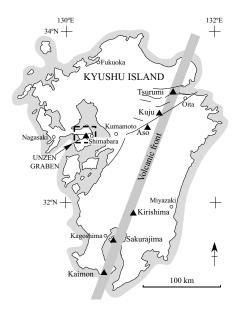


Figure 1 Location of Unzen Volcano. Solid triangles denote active volcanoes. Those distributed along the volcanic front are typical island-arc type volcanoes caused by the Philippine Sea plate subducting beneath SW Japan, while the Unzen volcanoes are considered to relate to the active graben development in last 500 ka.

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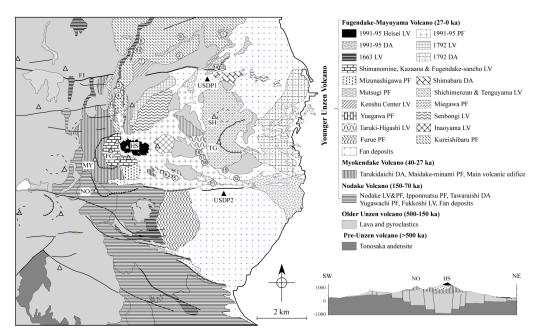


Figure 2 Geological map of Unzen Volcano modified from Watanabe and Hoshizumi (1995). A series of faults E-W in direction comprise Unzen graben (F1: Chichiwa fault). Unzen scientific drilling project boreholes (USDP-1 and 2) shown with solid triangles are located in the northern and central graben, respectively. Sample locations listed in Table 1 are indicated by open circles with numbers. Mountains: FG = Fugendake; HS = Heisei-Shinzan; MY = Myokendake; NO = Nodake; SH = Schichimenzan; TG = Tenguyama.

Unzen Volcano developed in the EW-trending tectonic graben within the back of the Ryuku arc in SW Japan. Synchronous development of nested normal faults during the growth of Unzen Volcano has resulted in the periodic subsidence of the main edifice and the accumulation of thick volcanic products down to ~1 km below sea level. As a result, no stratigraphic relationships between the volcanic products can be observed directly. The present stratigraphy of the eruption products was therefore established roughly by 2 locally exposed key-mark tephras (Kikai-Ah ash: 7.3 cal ka BP, and Aira-Tn ash: 29 cal ka BP, both of which originated from southern Kyushu; Machida and Arai 1983; Okuno et al. 1997, 1998) and sparsely accumulated radiometric ages using K-Ar (Ono et al. 1992; Watanabe et al. 1993; Hoshizumi et al. 1995, 1999), fission track (FT, Danhara et al. 1993), thermoluminescence (TL, Takashima and Watanabe 1994; Shimao et al. 1999; Yamagata et al. 2004; Moriyasu et al. 2008), and radiocarbon dating (Kobayashi and Kato 1986; Kobayashi and Nakada 1991; Hoshizumi et al. 1999; Xu et al. 2004; Ozeki et al. 2005). It is well known that the data from radiogenic methods other than ¹⁴C dating are typically imprecise for young materials. However, the scarcity of charcoal in Unzen Volcano made it difficult to apply the ¹⁴C method. Kobayashi and Nakada (1991) dated burned trunk pieces scattered in the Kureishibaru pyroclastic flows with ages of 14 and 19 ka BP, and a 14C age of 4.5 ka BP from 2 burned trunks in the Mizunashigawa pyroclastic flow. An average ¹⁴C age 4.3 ka BP from 3 charcoals from the Mutsugi pyroclastic flow deposits has been obtained (Kobayashi and Kato 1986; Hoshizumi et al. 1999; Ozeki et al. 2005). Obviously, these data are not enough to document the eruption history of the Younger Unzen Volcano. Moreover, the scarcity of charcoal in Unzen Volcano required us to examine the 14C dates on the buried soil organic carbon of bulk sample underlying the volcanic eruption products instead, as the age of buried soil can potentially represent the accumulation time of overlying materials that quickly accumulated (Orlova and Panychev 1993; Okuno et al. 1997; Okuno and Nakamura 2003).

MATERIALS AND METHODS

Charcoal and soil samples were used for 14 C dating in this study. Sampling locations are given in Table 1 and Figure 2. Charcoals were collected from the volcanic lava, pyroclastic flow, and pumice deposits of the Fugendake and Mayuyama volcanoes. Soil samples were collected from the topmost (<2 cm) soil underlying the volcanic-related products including lava, pyroclastic flow, ash, and lahar flow deposits. Care was always taken to minimize any effect from the roots of modern plants. Soil samples were first sieved and fractions with <106- μ m mesh were used. Charcoal and soil samples were chemically treated by routine acid-alkali-acid (AAA) methodology. After the chemical treatment, soil organic carbon was further separated into humic acid and humin fractions. The detailed procedure of chemical treatment, graphite target preparation, δ^{13} C determination, and 14 C AMS measurement has been described previously (Xu and Zheng 2003).

RESULTS AND DISCUSSION

Conventional 14 C and δ^{13} C results for the charcoal and soil samples are listed in Table 1. The 14 C ages were corrected for isotope fractionation using δ^{13} C values and blanks. The stated uncertainties (1σ) of 14 C ages include both the statistical uncertainty and the reproducibility of the standards and blanks. To compare with other radiometric dating methods, Table 1 also lists the calibrated age ranges (2σ) and median ages calculated using the OxCal v 4.1 program (Bronk Ramsey 2009) and the IntCal09 curve (Reimer et al. 2009). Duplicate analysis was done on 2 charcoal samples (JNC1421 vs. 1427, and JNC1431 vs. 1934), and a humic acid fraction of a humic soil sample (JNC1699 vs. 1708). Their δ^{13} C values and 14 C ages were consistent within the error margin.

Validity of ¹⁴C Dating Buried Soils

In alluvial and flood deposits, where soil burial occurs relatively quickly, and where the thickness of overlying sediments is sufficiently great to remove the buried soil from the zone of penetration of the present root system, ¹⁴C dates of soil organic fraction have been declared theoretically valid (Orlova and Panychev 1993; Braitseva et al. 1993; Madeira et al. 1997; Goto et al. 2011). In volcanic areas, soil burial is usually quick and typically the thickness of overlying volcanic deposits (pyroclastic, lava, and lahar flow deposits) are sufficiently great. Thus, the physical structure of volcanic deposits preserves soil organics and prevents soil organic matter movement along the depth profile. We therefore consider that ¹⁴C dates of soil immediately below the volcanic deposits to be representative of the time when the deposits covered the soil, namely, eruption and/or accumulation age. In practice, ¹⁴C dates from soil below the tephra layers in southern Kyushu Island showed good agreement with one other and are also consistent with the dates for charcoal and historical dates (Okuno et al. 1997, 1998; Okuno and Nakamura 2003), However, ¹⁴C dating of the bulk soil organic matter is always a problematic subject, mainly due to the complexity of the soil formation and to the variable contamination from different sources. Many researchers have qualitatively explained the age discrepancy between organic fractions of soil (e.g. Scharpenseel 1979; Orlova and Panychev 1993; Martin and Johnson 1995). Although traditionally the humic acid fraction was thought to yield younger ¹⁴C ages than humin fraction in routine AAA chemical treatment, later literature has questioned this inference (e.g. Head et al. 1989; Hamnond et al. 1991; Orlova and Panychev 1993). Thus, the question still arises of which fraction age is more reliable in the case of an age difference in soil organic matter fractions. It is well agreed that any fractions should contain relatively high organic carbon (Scharpenseel 1979). Okuno et al. (1997) also discussed the reliability of a soil sample with carbon content and C/N ratios and concluded that a high C/N ratio is one of the promising indications of reliable ¹⁴C dates. Based on these arguments, ¹⁴C ages of humic acid and humin fractions were considered and compared in this study.

Table 1 AMS ¹⁴C dates for the Fugendake and Mayuyama volcanoes.

	ì								Median	Lab
S	Sample ID	Long & Lat	Location	Samule time and description	Material	8 ¹³ C 14	¹⁴ C age (BP)	14 C age ^a (cal RP)	age ^a	code (INC-)
66	99111002	130°20′39″, 32°47′48″	Uto	Soil underlying the Aira-Tn ash	Humin	-21.0 2	4,696 ± 115	$-21.0 \ 24,696 \pm 115 \ 30,044 - 29,253 \ 29,649$	29,649	1465
6	99110801	130°19′21″, 32°47′21″,	Tateno	Charcoal inside the Kureishibaru PF	Humic acid Charcoal	-21.9 2: -20.3 1	$5,710 \pm 129$ $8,450 \pm 110$	Humic acid -21.9 $25,710 \pm 129$ $30,882 – 30,267$ $30,575$ Charcoal -20.3 $18,450 \pm 110$ $22,345 – 21,555$ $21,950$	30,575 21,950	1433 1421
6	99110802	130°19′21″, Tateno 32°47′21″	Tateno	Soil underlying the Kureishibaru PF	Humin	-20.5 13 -22.7 13	$-20.5 ext{ } 18,218 \pm 79$ $-22.7 ext{ } 18,390 \pm 84$	22,122–21,442 21,782 22,281–21,542 21,912	21,782 21,912	1427 1459
5	99110803	130°19′21″, Tateno 32°47′21″	Tateno	Soil underlying a volcanic ash	Humic acid Humin		$-23.4 18,591 \pm 96$ $-22.9 19,220 \pm 84$	22,477–21,766 22,122 23,361–22,506 22,934	22,122 22,934	1423 1458
$\overline{}$	00022702	130°19′21″, Tateno 32°47′21″	Tateno	Sandy loam underlying the Ippommatsu PF	Humic acid Humin	-23.4 -26.3	$-23.4 19,326 \pm 84$ $-26.3 23,339 \pm 100$	23,431–22,601 23,016 28,517–27,852 28,185	23,016 28,185	1422 1700
•	99110903	130°17′56″, 1 32°47′00″	Kenshu Center	Kenshu Center Charcoal inside the Yuegawa PF	Humic acid Charcoal	-25.9 2: -24.8 1:	$25,394 \pm 120$ $13,699 \pm 78$	$-25.9 25,394 \pm 120 30,540-30,130 30,335$ $-24.8 13,699 \pm 78 17,036-16,631 16,834$	30,335 16,834	1705 1427
•	9911090302		Kenshu Center	Kenshu Center Sandy loam underlying the Yuegawa PF	Humin	-24.3	99 = 6688	10,206–9746	9266	1462
٠,	99110804	130°17′58″, 32°46′47″	Kenshu Center	Kenshu Center Charcoal inside the Yuegawa PF	Humic acid Charcoal		-25.4 6629 ± 59 -24.8 $13,650 \pm 64$	7590–7430 7510 16,991–16,596 16,794	7510 16,794	1428 1424
$\overline{}$	00113004	130°17′58″, 32°46′47″	Kenshu Center	Kenshu Center Soil underlain the Yuegawa PF	Humin	-22.0 13	$-22.0 13,432 \pm 61$	16,879–16,136 16,508	16,508	2453
\circ	00120201	130°19′19″, 32°44′50″	Tansanmi-	Charcoal inside the Yuegawa PF	Humic acid Charcoal		$-24.3 13,826 \pm 48$ $-26.7 13,908 \pm 63$	17,099–16,755 16,927 17,191–16,783 16,987	16,927 16,987	2494 2449
0	00120203	130°19′17″, 32°44′51″	Tansanmi- zutani	Charcoal inside the Yuegawa PF	Charcoal	-20.7 13	$-20.7 \ 13,041 \pm 66$	16,385–15,175 15,780	15,780	2450
\circ	00120202	130°19′17″, 32°44′51″	Tansanmi- zutani	Soil underlying the Yuegawa PF	Humin	-20.4 1	$-20.4\ 14,253 \pm 58$	17,643–17,006 17,325	17,325	2570
2/	99110906	130°18′17″, 32°47′14″	Kenshu Center	130°18'17", Kenshu Center Charcoal inside the Kenshu Center IV 32'47'14"	Humic acid -21.5 13,758 ± 59 Charcoal -27.5 10,454 ± 55	-21.5 1: -27.5 10	$13,758 \pm 59$ $10,454 \pm 55$	17,056–16,710 16,883 12,562–12,128 12,345	16,883 12,345	2704 1431
						-27.9 10	$-27.9 \ 10,471 \pm 45$	12,576–12,145 12,360	12,360	1934

Table 1 AMS ¹⁴C dates for the Fugendake and Mayuyama volcanoes. (Continued)

									Median	Lab
Site		Long & Lat				813C	¹⁴ C age	$^{14}\mathrm{C}~\mathrm{age^a}$	age^a	
nr	Sample ID	(E, N)	Location	Sample type and description	Material	(%)	(BP)	(cal BP)	(cal BP)	(JNC-)
∞	99110901	130°18′20″, 32°47′35″		Kenshu Center Soil underlying the Miegawa PF	Humin	-21.6	9833 ± 51	11,352–11,177 11,265	11,265	1460
6	00022901	130°19′28″, 32°47′45″	130°19′28″, Hirotakano 32°47′45″	Soil underlying a lahar	Humic acid Humin	-22.5 -23.8	$10,036 \pm 55$ $11,380 \pm 60$	11,776–11,286 11,531 13,380–13,125 13,253	11,531 13,253	1425 1704
10	99110902	130°18′17″,	Kenshu Center	Kenshu Center Soil underlying a lahar	Humic acid Humic acid Humin	-25.4 -24.8 -22.3	$11,284 \pm 49$ $11,331 \pm 50$ $10,103 \pm 49$	13,304–13,091 13,321–13,111 11,973–11,405	13,198 13,216 11,689	1699 1708 1461
;		32°47′32″	;	:	Humic acid		$10,251 \pm 55$	∞	12,067	1426
Ξ	00113001	130°20′20″, 32°40′40″	Nakaonokoba	Charcoal inside a pumice	Charcoal	-26.2	8640 ± 46	9700–9532	9196	2448
12	00120302a	130°20′36″, 32°44′45″	Minami- Kamikoba	Charcoal inside the Mizunashigawa PF	Charcoal	-27.0	3877 ± 28	4416–4186	4301	2723
13	UZW01	130°20′50″, 32°47′31″	Uto	Charcoal inside the Mutsugi PF	Charcoal	-29.7	3762 ± 32	4238–3994	4116	1319
4	00022803	130°20′31″, 32°47′09″	Kamioribashi	Sandy loam between the Mutsugi pfd Shimabara DA	Humin	-24.1	6573 ± 42	7566–7426	7496	1703
	00113002	130°20′31″, 32°47′09″	Kamioribashi	Sandy loam between the Mutsugi pfd Shimabara DA	Humin	-21.4	5009 ± 49	5900–5646	5773	2567
15	00022802	130°20′40″, 32°45′05″	Kitakamimoku	Sandy loam underlying the Tenguyama LV Humin	Humin	-25.4	4520 ± 46	5316–5039	5178	1702
16	99111005	130°20′02″, 32°45′18″	130°20′02″, Kitakamikoba 32°45′18″	Soil underlying a likely pfd and overlaying a lahar	Humic acid –25.1 Humin –22.7	-25.1 -22.7	1784 ± 40 661 ± 42	1821–1574 678–552	1698	1706 1468
	99111004	130°20′02″, 32°45′18″	Kitakamikoba	Soil underlying a lahar	Humic acid –23.2 Humin –22.0	-23.2 -22.0	633 ± 58 1658 ± 35	675–536 1692–1418	606 1555	1436 1467
17	99111007	130°20′10″, 32°45′17″	130°20′10″, Kitakamimoka 32°45′17″	Soil between a lahar and the Mayuyama products	Humic acid Humin	-23.9 -21.6	1668 ± 34 1712 ± 37	1694–1423 1705–1540	1559 1623	1435 1470
18	99111006	130°20′10″,	130°20′10″, Kitakamimoka 32°45′17″	Soil between a lahar and the Mayuyama products	Humic acid Humin	-23.0 -22.2	1728 ± 35 1752 ± 30	1713–1547 1736–1561	1630 1649	1438 1469
					Humic acid -23.4	-23.4	1729 ± 60	1815–1526	1671	1437
1.08	The second second second		0.1.7	001 071 171 00000	(000					

^aCalibrated age ranges are calculated using OxCal v 4.1 (Bronk Ramsey 2009) and the IntCal09 curve (Reimer et al. 2009).

Table 1 shows that all humic soil samples gave coeval 14 C dates on the humic acid and humin fraction within the 2σ error margin in each soil horizon. Aira-Tn ash is widespread co-ignimbrite ash-fall deposits from Aira caldera of 29 ka cal BP (Okuno 2002; Okuno and Nakamura 2003). As shown for site 1 (Figures 2 and 3), the 14 C ages of both soil fractions underlying the Aira-Tn ash, 29–30 cal ka BP (JNC1433 and 1465), are in good agreement with the nominal value. In the soil-volcanic products profile where charcoal is available, the soil 14 C dates are essentially identical to the charcoal ages. This finding strongly supported that the age of both organic fractions of buried humic soil can potentially represent accumulation time of overlying materials that have quickly accumulated (Orlova and Panychev 1993; Okuno et al. 1997).

It should be noted, however, that sandy loam samples had large age discrepancies between organic fractions (i.e. JNC1700 vs. 1705, JNC1462 vs. 1428, JNC1702 vs. 1706). The sandy loam underlying the Ippommatsu pyroclastic flow deposits dated to 23.339 ± 100 BP (JNC1700) and $25,394 \pm 120$ BP (JNC1705) for the humin and humic acid fraction, respectively. As the Ippommatsu pyroclastic flow deposits were covered by Aira-Tn ash (29 cal BP) in the stratigraphic section, the soil underlying the Ippommatsu pyroclstic flow deposits should be significantly older than the Aira-Tn ash. However, this is not the case. A thin sandy loam layer (~10 cm) was observed underlying the Tenguyama lavas (site 15). This sample gave ages of 4520 ± 46 BP (JNC1702) and 1784 ± 40 BP (JNC1706) for the humin and humic acid fraction, respectively. Obviously, although the humin age is consistent with the TL date for the Tenguyama lava $(4.1 \pm 0.8 \text{ kg})$, Yamagata et al. 2004), it is significantly older than humic acid fraction, which makes it difficult to justify the validity of the data. Moreover, no humic acid fractions can be extracted from the sandy loam samples (JNC1703 and 2567) collected in different times from the top of a ~50-cm-thick sandy loam layer between the Mutsugi pyroclastic flow deposit and the Shimabara debris avalanche (site 14). The ¹⁴C ages of the humin fraction of 2 samples were 6573 \pm 42 BP (JNC1703) and 5009 \pm 49 BP (JNC2567). These discrepant dates were significantly older than the age of the overlying Mutsugi pyroclastic flow deposits whose age is most likely around 4 ka BP, as referred from the adjacent sites (Kobayashi and Kato 1986). These observations therefore strongly suggest that any fractions of sandy loam sample are not reliable material for ¹⁴C dating of volcanic eruptions. Although the details of the mechanism are not yet clear, a low carbon content in sandy loam seems to be more sensitive to contamination from modern carbon, as observed elsewhere (Scharpenseel 1979; Okuno et al. 1997). With these considerations, we can interpret the data in Table 1 and discuss the eruption age of the Fugendake and Mayuyama volcanoes using 14C dates obtained from charcoal and/or humic soil that has coeval humic acid and humin ages.

Radiocarbon Dating of the Fugendake-Mayuyama Volcano

Fugendake Volcano was developed inside and outside of the Myokendake scar (Figure 2). Field investigations divided the Fugendake Volcano into several lava flows (L), lava domes, and pyroclastic flow deposits (PF), and 1 debris-avalanche (DA) deposit (Watanabe and Hoshizumi 1995). Mayuyama Volcano, located at the easternmost part of Unzen Volcano, comprises 2 huge lava domes of hornblende dacite and 1 pyroclastic flow deposit. As the rifting-induced subsidence in the Unzen graben makes it difficult to positively identify the initial eruption at the surface, and directly observe stratigraphic relation between these eruption products, establishment of the Unzen volcanic history significantly relies on precise chronological control (Table 1 and Figure 4).

23ka Eruptions: Furue L - Kureishibaru PF - Taruki-higashi L

The Kureishibaru pyroclastic flow deposit of hornblende dacite spreads widely over the northern and northeastern slopes of Fugendake. In site 2, 1 charcoal sample collected inside the Kureishibaru

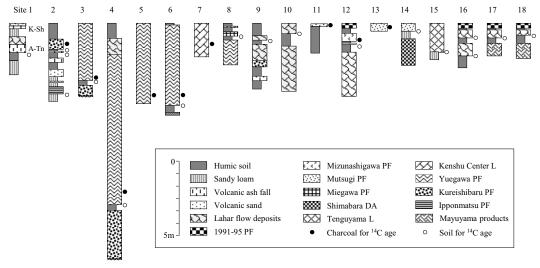


Figure 3 Representative stratigraphic sections around the Fugendake and Mayuyama volcanoes. Sites from 1 to 18 are shown in Figure 2. AT and K-Ah are widespread co-ignimbrite ash-fall deposits from Aira caldera of 29 cal ka BP, and Kikai caldera of 7.3 cal ka BP, respectively.

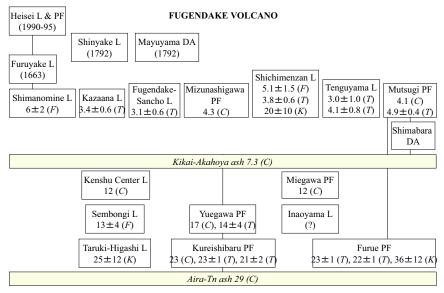


Figure 4 Diagram showing the stratigraphy of the Fugendake and Mayuyama volcanic products. Vertical lines show the stratigraphic relation observed at outcrops. L: lava flow; PF: pyroclastic flow; DA: debris avalanche; C: calibrated ¹⁴C age; T: TL age; K: K-Ar age; F: fission track age.

pyroclastic flow gave an age of $18,334 \pm 134$ BP averaged by duplicate analysis (JNC1421 and 1427). This age is consistent with an underlying soil sample whose humin and humic acid fraction ages were $18,390 \pm 84$ BP (JNC1459) and $18,591 \pm 96$ BP (JNC1423), respectively. These ages are consistent with the previous ¹⁴C results: 19 ka BP (Kobayashi and Nakada 1991) and $18,850 \pm 180$ BP (Hoshizumi et al. 1999). Moreover, the ¹⁴C dates (~22 cal ka BP) are comparable with 2 TL ages: 23 ± 1 ka (Shimao et al. 1999) and 21 ± 2 ka (Moriyasu et al. 2008). The ¹⁴C ages observed at the

surface are also consistent with those measured at USDP1 borehole (Figure 2). The humic soils underlying volcanic-related lahar flow deposits at depth of 56.42 m of the USDP-1 borehole gave a ¹⁴C age of 18.8 ka BP (Xu et al. 2004), suggesting that the accumulation of the lahar flow deposits was caused by the Kureishibaru pyroclastic eruption.

In the same soil-volcanic stratigraphic sequence in site 2, 1 soil sample underlying a thin volcanic ash layer gave an age of $19,220 \pm 84$ BP (humin, JNC1458) and $19,326 \pm 84$ BP (humic acid, JNC1422), slightly older than the overlying Kureishibaru pyroclastic flow deposits. Although the volcanic ash is not sufficiently great, the coeval 14 C dates on humic acid and humin fraction and normal stratigraphical relation implied that the closed 14 C system may have retained.

Similar to the Kureishibaru pyroclastic flow deposit, the Furue lavas are an andesite block-and-ash flow deposit spread on the southeastern flank of the Fugendake. Hoshizumi et al. (1995, 1999) obtained 2 K-Ar ages of 36 ± 12 and 67 ± 14 ka, much older than the covering Aira-Tn ash (cal 29 ka). However, 2 consistent TL dates were obtained: 23 ± 1 ka (Shimao et al. 1999) and 22 ± 1 ka (Moriyasu et al. 2008). The Taruki-higashi lavas are lava domes of hornblende dacite erupted on the eastern flank of the Fugendake. One K-Ar dating (25 ± 12 ka) was obtained from the Taruki-higashi lava (Hoshizumi et al. 1995, 1999).

17ka Eruptions: Inaoyama L - Sembongi L - Yuegawa PF

There are many charcoals in the Yuegawa pyroclastic flow deposits. In site 3, 1 charcoal inside the Yuegawa pyroclastic flow deposits gave an age of 13,699 ± 78 BP (JNC1427). However, as described above, the sandy loam below the pyroclastic flow showed scattered, young ages, $8899 \pm$ 66 BP (JNC1462) and 6629 ± 59 BP (JNC1428) for humin and humic acid fractions, respectively. In contrast, at site 4, 1 charcoal gave a 14 C age of 13.650 ± 64 BP (JNC1424), and humic soil below the pyroclastic flow showed consistent ages of $13,432 \pm 61$ BP (JNC2453) and $13,826 \pm 48$ BP (JNC2494) for the humin and humic acid fractions, respectively. In site 5, 1 charcoal gave an age of $13,908 \pm 63$ BP (JNC2449). Similar results can be found in site 6, where 1 charcoal gave an age of $13,041 \pm 66$ BP (JNC2450), and humic soil below the pyroclastic flow showed consistent ages, $14,253 \pm 58$ BP (JNC2570) and $13,758 \pm 59$ BP (JNC2704) for the humin and humic acid fractions, respectively. These dates are consistent with a ¹⁴C age of 14 ka BP obtained by Kobayashi and Nakada (1991). Furthermore, these 14 C ages are comparable with a TL age of 14 ± 4 ka (Moriyasu et al. 2008). The Yuegawa pyroclastic flow age is also comparable with a fission track age of $13 \pm$ 3 ka from the Sembongi lava flow (Danhara et al. 1993). The Senbongi lava is a thick lava flow of hornblende andesite exposed on the flank of the Myokendake. Although there is no date available for the Inaoyama lava yet, these dates seem to collectively suggest that the products at 17 ka had originated from Fugendake Volcano.

12ka Eruptions: Kenshu Center L - Miegawa PF

In site 7 (Figure 2), a charcoal sample was found in the Kenshu Center lava flow. Duplicate analyses gave ages of $10,454 \pm 55$ (JNC1431) and $10,471 \pm 45$ BP (JNC1934), for an average age of $10,462 \pm 36$ BP. It should be noted that this lava flow was initially classified into the Older Unzen volcanics based on K-Ar dates (Watanabe and Hoshizumi 1995; Hoshizumi et al. 1999). However, a 14 C date obtained here is significantly younger than the upper limit of the Old Unzen volcanics (150 ka). This finding is compatible with previously published K-Ar dates and supported by geological observations. Watanabe et al. (1993) obtained a K-Ar age of 1.33 ± 0.73 Ma for a hornblende dacite. Duplicate analyses of a hornblende dacite also gave ages of 0.50 ± 0.35 and 0.50 ± 0.38 Ma (Ono et al. 1992). These K-Ar dates are in the range of the Older Unzen volcanics within 1σ error margin.

However, if using the 2σ error margin for the most reasonable consideration, these K-Ar dates are all beyond the determination limit of K-Ar dating and thus suggest ages close to zero. Geological investigations indicated that the W-E-trending Chichiwa fault, one of the major boundary faults of Unzen graben (F1 in Figure 2), disappears in the north of Rokiyama where the Older Unzen volcanics are distributed (Figure 2). This strongly suggests that the Chichiwa fault distributed in the north of Rokiyama should be overlain by younger volcanic products (<150 ka). The age of 10 ka BP obtained from the charcoal thus enabled us to conclude that the Kenshu Center lava flow deposit is a product of the Younger Unzen volcanics. This is also supported by ¹⁴C dating of the Miegawa proclastic flow and volcanic-related lahar flow deposits in several adjacent sites. In site 8, a humic soil layer is covered by the Miegawa pyroclastic flow deposits. The humin and humic acid ¹⁴C ages are 9833 ± 51 BP (JNC1460) and $10,036 \pm 55$ BP (JNC1425), respectively. In site 9, the humic soil underlying a volcanic-related lahar flow deposits gave consistent 14 C ages for humin, $11,380 \pm 60$ BP (JNC 1704), and the duplicate humic acid 11,284 \pm 49 BP (JNC1699) and 11,331 \pm 50 BP (JNC1708). In site 10, humin and humic acid fractions of burial soil underlying a lava gave similar 14 C ages of $10,103 \pm 49$ BP (JNC1461) and $10,251 \pm 55$ BP (JNC1426), respectively. All these dates indicated simultaneous volcanic products originating from Fugendake Volcano around 10 ka BP (12 cal ka BP).

4.5ka Eruptions: Fugendake-sancho L – Kazaana L – Mizunashigawa PF – Mutsugi PF – Shichimenzan L – Shimanomine L – Tenguyama L

At the Fugendake-sancho (summit of Fugendake), the Kazaana and the Shimanomine lavas are composite lava domes of andesite to dacite composition extruded inside the Myokendake scar. The Mizunashigawa pyroclastic flow deposit is also an andesite block-and-ash flow deposit covering part of the SE flank of the Fugendake. These volcanic products were considered to have originated from Fugendake Volcano. However, the Shichimenzan and Tenguyama lavas and Mutsugi pyroclastic flow deposit are isolated from Fugendake Volcano and comprise Mayuyama Volcano.

Yamagata et al. (2004) reported a TL age of 3.1 ± 0.6 ka from the Fugendake-sancho lava and 3.4 ± 0.6 ka from the Kazaana lava. The Shimanomine lava was dated at 6 ± 2 ka by the fission-track method (Danhara et al. 1993). Charcoals from the Mizunashigawa pyroclastic flow deposit have been dated to ~4 ka BP by 14 C (Kobayashi and Nakada 1991; Ozeki et al. 2005). Our result of a charcoal from the Mizunashigawa pyroclastic flow deposit in site 12 gave an age of 3877 ± 28 BP, comparable with these dates.

Located at the easternmost part of Unzen Volcano, Mayuyama Volcano comprises 2 huge lava domes of hornblende dacite: Shichimenzan and Tenguyama. A zircon fission-track date for the Shichimenzan lava is 5.1 ± 1.5 ka (Danhara et al. 1993). A K-Ar age of 20 ± 10 ka was also reported for the Shichimenzan lava (Watanabe et al. 1993). Two TL dates for Shichimenzan and Tenguyama lavas are 3.8 ± 0.6 and 4.1 ± 0.8 ka, respectively (Yamagata et al. 2004). The Mutsugi pyroclastic flow deposit is a block-and-ash flow deposit of hornblende dacite derived from the northern part of Mayuyama dome (Hoshizumi et al. 1999). In this study, we obtained a charcoal 14 C age of 3762 ± 32 BP (JNC1319) from the Mutsugi pyroclastic flow deposit (site 13), which is significantly younger than the previous results of 4220 ± 110 yr BP (Hoshizumi et al. 1995) and 4.0 ka BP (Kobayashi and Kato 1986). Field observations indicated that there are 2 units with different eruption styles, the large block in the upper and a smaller one in the lower unit. No soil layer was observed between the 2 units, which suggests either the condition of unfavorable vegetation growth or a short interval between 2 volcanic episodes. The discrepant ages obtained from this study and previous dates may represent 2 volcanic episodes of the Mutsugi pyroclastic flow deposit.

Mayuyama Volcano was thus active during the building stage of Fugendake Volcano at 4.5 ka and built on the eastern extension of Fugendake. This suggests that magma more felsic than those of Fugendake Volcano was supplied through the same EW-trending extensional fault system, but probably from a different magma reservoir or a more differentiated part of the same reservoir.

Possible Events of Volcanic Eruptions and Lahar Accumulations

Few pumice deposits were found scattered in the west bank of Mizunashigawa (site 11 in Figure 2). One charcoal was found inside the pumice deposits and 14 C dated to 8640 ± 46 BP, or 9.6 cal ka BP (JNC2448). If this new date represented a volcanic event, the corresponding eruption would be instantaneous and of limited scale.

There are 2 humic soil layers underlying the lahar deposits (site 16 in Figure 3). The upper soil produced 14 C ages of 661 ± 42 BP (JNC1468) and 633 ± 58 BP (JNC1436) for the humin and humic acid fractions, respectively, while the lower resulted in ages of 1658 ± 35 BP (JNC1467) and 1668 ± 35 BP (JNC1435). The calibrated 14 C age of the upper soil was 610 cal BP (AD 1340). However, there are no available records to confirm if this event was an unidentified volcanic eruption or a non-volcanic landslide. The lower soil is comparable with those observed in adjacent sites. In site 17, a soil sample underlain by a lahar deposit was dated with 14 C ages of 1712 ± 37 BP (humin, JNC1470) and 1728 ± 35 (humic acid, JNC1438). Another layer of soil nearby (site 19) also produced 14 C ages of 1752 ± 30 BP (JNC1469) and 1729 ± 60 BP (JNC1437) for the humin and humic acid fractions, respectively. More field investigations and dating are needed to clarify if these lahar accumulations were volcanically related.

Outline of the Fugendake-Mayuyama Volcanic History

Based on the present and previous dates, together with detailed field investigations, the history of the Fugendake-Mayuyame volcanoes can be outlined (Figure 4). Fugendake Volcano erupted mainly within the Myokendake crater. The eruption started about 29 ka, probably immediately after the collapse of Myokendake Volcano. The first eruption product is not positively identified, however. Hoshizumi et al. (1999) proposed that it may be the Taruki-higashi lava based on the K-Ar date (25 ± 12 ka). This hypothesis is supported by ¹⁴C ages of a humic soil layer underlying a pyroclastic flow deposit at 71.60–71.90 m depth of the USDP-2 borehole near the Taruki terrace (Figure 2). The topmost soil gave a ¹⁴C age of 29 cal ka BP, suggesting the initial activity of Fugendake Volcano (Xu et al. 2004). With the eruptive interval of 5–6 ka, lava flows and lava domes were intermittently produced around 22, 17, 12, and 4.5 ka ago, and more recently in AD 1663, 1792, and 1991–1995. Several block-and-ash flows and 1 debris avalanche were accordingly generated by dome collapse processes. On the other hand, Mayuyama Volcano had only 1 simultaneous eruption around 4.5 ka when Fugendake Volcano was active. Hoshizumi et al. (1999) have estimated that the total eruptive volume of Fugendake and Mayuyama is ~3 km³.

CONCLUSIONS

¹⁴C ages of humin and humic acid fractions of a buried humic soil immediately underlying the thick volcanic products appear almost coeval and can represent the eruption or accumulation date. However, sandy loam is not an ideal material to reflect eruptive events. Fugendake Volcano had initiated most likely around 29 ka with large intermittent eruptive events occurring at 22, 17, 12, and 4.5 ka, and more recently in AD 1663, 1792, and 1991–1995. Mayuyama Volcano was built around 4.5 ka when Fugendake Volcano was active.

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REFERENCES

- Braitseva OA, Sulerzhitsky LD, Litasova SN, Melekestsev IV. 1993. Radiocarbon dating and tephrochronology in Kamchatka. *Radiocarbon* 35(3):463–76.
- Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337–60.
- Danhara T, Iwano H, Hoshizumi H, Watanabe K. 1993.
 Fission track dating of very young zircon from the Unzen Volcano. Programe and Abstract of Volcanological Society of Japan 2:51. In Japanese.
- Goto Y, Gouchi N, Matsuda I. 2011. Radiocarbon dating of the Minamidake debris-avalanche deposit, Shiretoko-iozan volcano, Eastern Hokkaido, Japan. Bulletin of the Volcanological Society of Japan 56: 161–7.
- Hamnond AP, Goh KM, Tonkin PJ, Manning MR. 1991. Chemical pretreatments for improving the radiocarbon dates of peat and organic silts in a gley podzol environment: Grahams Terrace, North Westland. New Zealand Journal of Geology and Geophysics 34:181–94
- Head MJ, Zhou W, Zhou M. 1989. Evaluation of ¹⁴C ages of organic fractions of paleosols from loess-paleosol sequences near Xian, China. *Radiocarbon* 31(3):680– 96.
- Hoshizumi H, Uto K, Watanabe K. 1995. K-Ar age determination for Unzen volcano: volcanic history of Unzen volcano. *Programe and Abstract of Volcanological Society of Japan* 2:99. In Japanese.
- Hoshizumi H, Uto K, Watanabe K. 1999. Geology and eruptive history of Unzen volcano, Shimabara Peninsula, Kyushu, SW Japan. *Journal of Volcanology and Geothermal Research* 89:81–94.
- Kobayashi T, Kato W. 1986. Formation history of Unzen volcano. Programe and Abstract of Volcanological Society of Japan 2:77. In Japanese.
- Kobayashi T, Nakada S. 1991. ¹⁴C ages of pyroclastic flow and avalanche deposits and the history of Unzen volcano. *Programe and Abstract of Volcanological Society of Japan* 2:140. In Japanese.
- Machida H, Arai F. 1983. Extensive ash falls in and around the Sea of Japan from large late Quaternary eruptions. *Journal of Volcanology and Geothermal Research* 18:151–64.
- Martin CW, Johnson WC. 1995. Variation in radiocarbon ages of soil organic matter fractions from late Quaternary buried soils. *Quaternary Research* 43(2): 232–7.

- Madeira J, Monge Soares AM, Brum Da Silveira A, Serralheiro A. 1997. Radiocarbon dating recent volcanic activity on Faial Island (Azores). *Radiocarbon* 37(2): 139–48.
- Moriyasu M, Okuno M, Takashima I, Nagaoka S, Sakaguchi K, Aizawa J. 2008. Thermoluminescence ages for the Furue, Kureishibaru and Yuegawa pyroclastic flow deposits in the Younger Unzen Volcano, SW Japan. Fukuoka University Science Report. p 53–62. In Japanese with English abstract.
- Okuno M. 2002. Chronology of tephra layers in Southern Kyushu, SW Japan, for the last 30,000 Years. *Quaternary Research* 41:225–36. In Japanese with English abstract.
- Okuno M, Nakamura T. 2003. Radiocarbon dating of tephra layers: recent progress in Japan. *Quaternary In*ternational 105(1):49–56.
- Okuno M, Nakamura T, Moriwaki H, Kobayashi T. 1997.
 AMS radiocarbon dating of the Sakurajima tephra group, Southern Kyushu Japan. Nuclear Instruments and Methods in Physical Research B 123(1–4):470–4.
- Okuno M, Nakamura T, Kobayashi T. 1998. AMS ¹⁴C dating of historic eruptions of the Kirishima, Sakurajima and Kaimondake volcanoes, Southern Kyushu, Japan. *Radiocarbon* 40(2):825–32.
- Ono K, Watanabe K, Itaya T, Hori S, Hoshizumi H, Hiyashi H, Otsudsuki H. 1992. Geology and K-Ar age of Unzen Volcano (preliminary report). *Programe and Abstract of Volcanological Society of Japan* 2:1. In Japanese.
- Orlova LA, Panychev VA. 1993. The reliability of radiocarbon dating buried soils. *Radiocarbon* 35(3): 369–77
- Ozeki N, Okuno M, Kobayashi T. 2005. Growth history of Mayuyama, Unzen Volcano, Kyushu, southwest Japan. *Bulletin of the Volcanological Society of Japan* 50:441–54. In Japanese.
- Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton T, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4): 1111–50.

- Scharpenseel HW. 1979. Soil fraction dating. In: Radiocarbon dating. In Berger R, Suess H, editors. *Proceedings of the 9th International Radiocarbon Conference*. Berkeley: University of California Press. p 277–83.
- Shimao T, Takashima I, Watanabe K, Izawa E. 1999. Verification of errors and reliability of thermoluminescence age for volcanic rocks -Precise beta-ray correction age of pyroclastic flow deposits of Unzen volcano, SW Japan. *Journal of Mineralogy, Petrology and Economic Geology* 94(4):109–19. In Japanese with English abstract.
- Takashima I, Watanabe K. 1994. Thermoluminescence age determination of lava flows/domes and collapsed materials at Unzen volcano, SW Japan. *Bulletin of the Volcanological Society of Japan* 39:1–12.
- Watanabe K, Hoshizumi H. 1995. Geological map of Unzen volcano (1:25,000). Geological map of volcanoes 8, Geological Survey of Japan. In Japanese with En-

- glish abstract.
- Watanabe K, Hoshizumi H, Itaya T. 1993. K-Ar ages of Unzen Volcano in Kyusyu, Japan with some aspects of geology of Mayuyama. *The Memoirs of the Faculty of Education, Kumamoto University* 42:35–41.
- Xu S. Zheng G. 2003. Variations in radiocarbon ages of various organic fractions in core sediments from Erhai Lake, SW China. Geochemical Journal 37(1):135–44.
- Xu S, Hoshizumi H, Ochiai Y, Aoki H, Uto K. 2004. ¹⁴C dating of soil samples from the Unzen volcano scientific drilling boreholes. *Nuclear Instruments and Methods in Physics Research B* 223–224:560–7.
- Yamagata T, Takashima I, Watanabe K, Izawa E. 2004. TL dating of new lava domes in Unzen volcano–activities history restoration toward the younger lava dome than 20,000 years. *Bulletin of the Volcanological Society of Japan* 49:73–81. In Japanese with English abstract.