Radiocarbon, Vol 59, Nr 2, 2017, p 483–488 DOI:10.1017/RDC.2016.66
Selected Papers from the 2015 Radiocarbon Conference, Dakar, Senegal, 16–20 November 2015

AMS RADIOCARBON DATES OF PYROCLASTIC-FLOW DEPOSITS ON THE SOUTHERN SLOPE OF THE KUJU VOLCANIC GROUP, KYUSHU, JAPAN

Mitsuru Okuno[1*] • Shinji Nagaoka[2] • Yoko Saito-Kokubu[3] • Toshio Nakamura[4] • Tetsuo Kobayashi[5]

[1]AIG Collaborative Research Institute for International Study on Eruptive History and Informatics; also Department of Earth System Science, Faculty of Science, Fukuoka University, Fukuoka 814-0180, Japan.
[2]Formerly Nagasaki University, Nagasaki 852-8521, Japan (passed away on 10 July 2011).
[3]Tono Geoscience Center, Japan Atomic Energy Agency, 959-31 Jorinji, Toki, Gifu 509-5102, Japan.
[4]Division for Chronological Research, Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan.
[5]Emeritus Professor, Kagoshima University, Kagoshima 890-0065, Japan.

ABSTRACT. The Kuju volcanic group, located in central Kyushu, Japan, consists of small stratovolcanoes and lava domes. To refine the eruptive history of the group, we conducted accelerator mass spectrometry (AMS) radiocarbon dating of charcoal fragments from three pyroclastic-flow (PF) deposits on the southern slope. The obtained ^{14}C dates are consistent with the geomorphology, stratigraphy, and thermoluminescence (TL) ages. The Handa PF deposits, which are products of the largest eruption of the group, were dated to ~53.5 ka BP. The Shirani and Muro PF deposits, which are block-and-ash flows, were dated to 44 to >50 cal ka BP and 35–39 cal ka BP, respectively. These ages can be correlated with TL ages for lava domes. This study demonstrates that the lava domes and associated PF deposits formed after the Handa eruption.

KEYWORDS: Kuju volcanic group, AMS radiocarbon dating, pyroclastic-flow deposits, lava dome.

INTRODUCTION

The Kuju volcanic group, located in central Kyushu, Japan (Figure 1a), consists of more than 20 small stratovolcanoes and lava domes (Kawanabe et al. 2015). In the central part of the group (Figure 1b), the majority of the lavas formed hornblende-andesitic and dacitic lava domes (Ohta 1991). Kamata and Kobayashi (1997) established the tephra-stratigraphy above the Aira-Tn (AT) ash (30 cal ka BP) and demonstrated its eruptive history through the last 15,000 yr using radiocarbon ages of paleosols intercalated with fallout tephras. However, the stratigraphic position of the lavas remained unclear due mainly to the difficulty of preserving tephra layers in the mountainous area.

Okuno et al. (2013) reported thermoluminescence (TL) ages of lava domes in the central area (Figure 1c). Subsequently, Nagaoka and Okuno (2014, 2015) revised the tephra-stratigraphy of the group (Figure 2). Here, we present accelerator mass spectrometry (AMS) ^{14}C dates of charcoal samples from pyroclastic-flow (PF) deposits to refine the history of the central part of the group.

METHODS AND MATERIALS

Outline of Geology in Central Part of Kuju Volcanic Group

Plinian eruptions formed the Kuju-D (also named Yutsubo) and Kj-P1 pumice-fall deposits, and have a volume of 6.6 km^3 (Figure 1a). During the Plinian eruptions, a portion of the eruption column collapsed and generated the Handa PF deposit (Kj-Hd). The Kj-Hd accumulated to a volume of 5 km^3. Both the Kj-P1 and Kj-Hd are continuous eruptive products of the typical intra-Plinian type (Nagaoka and Okuno 2015). This eruption, beginning with the Kuju-D pumice fall, is collectively named the Handa eruption (Figure 2). The total bulk volume of the erupted tephra could be ~12 km^3, corresponding to a volcanic explosivity index (VEI; Newhall and Self 1982) of 5 or 6. Therefore, it might have resulted in the formation

*Corresponding author. Email: okuno@fukuoka-u.ac.jp.

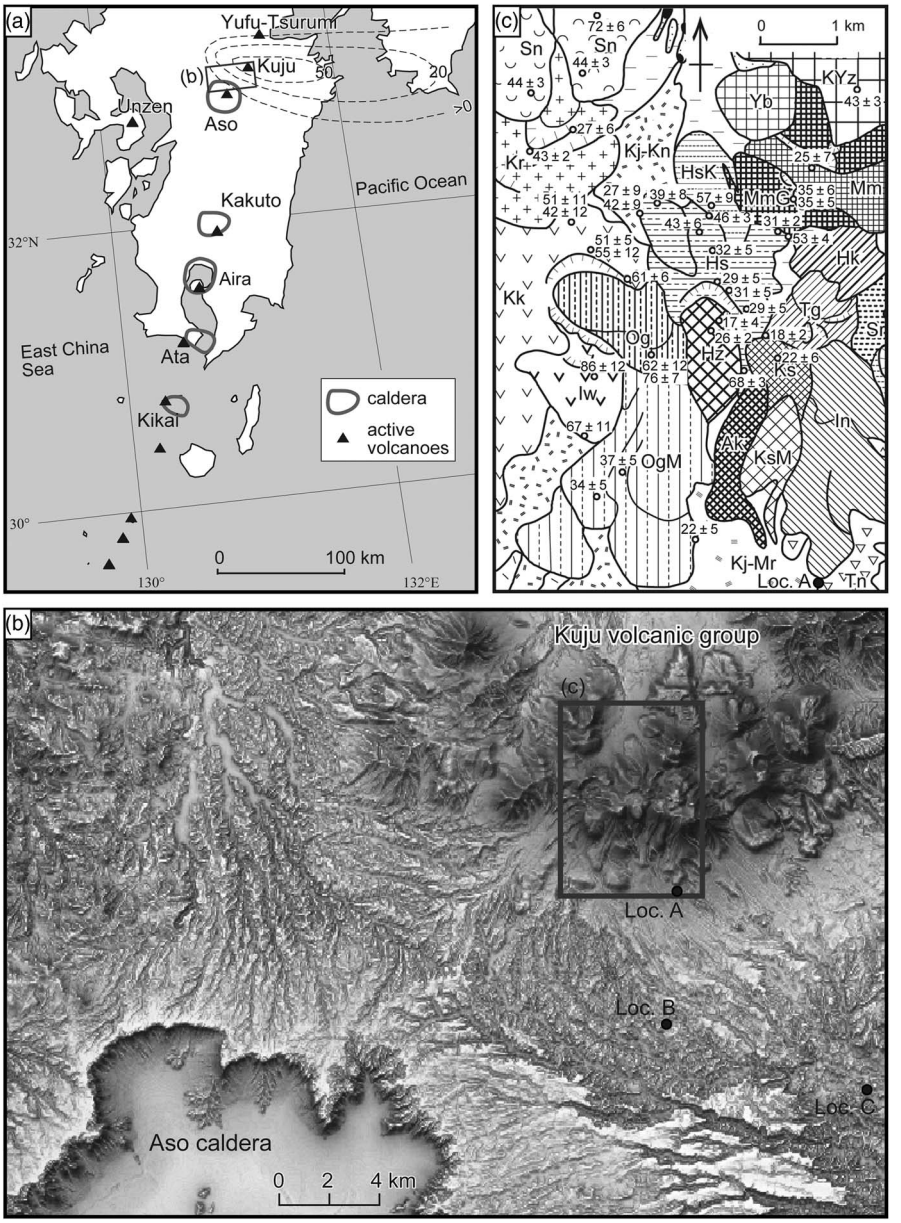

Figure 1 (a) Map showing the distribution of volcanoes on Kyushu Island. The rectangle indicates the area of part (b). Dashed lines show the distribution of the Kj-P1 tephra (Nagaoka and Okuno 2014). Values are in cm. (b) Topographic map of Kuju volcanic group and northern part of Aso caldera. Basement map was prepared by KASHIMIR 3D. The rectangle indicates the area of part (c). Locations A (33°3′21″N, 131°14′56″E), B (33°0′47″N, 131°14′53″E), and C (32°59′4″N, 131°19′44″E) are designated by solid circles. (c) Geological map of the central part of the Kuju volcanic group (modified from Nagaoka and Okuno 2015). Ak: Akagawa lava; Hs: Hosshozan lava; HsK: Hossho-kita lava; Hz: Hizengajo lava; In: Inaboshiyama lava; Iw: Iwaigodake lava; Kj-Hd: Handa PF deposits; Kj-Mr: Muro PF deposits; Kk: Kutsukakeyama lava; Kr: Kuroiwayama lava; Ks: Kujusan lava; KsM: Kuju-minami lava; KYz: Kami-Yuzawa lava; Mm: Mimatayama lava; MmG: Mimata-Gairinzan lava; Og: Ogigahana lava; OgM: Ogigahana-minami lava; Sn: Sensuizan lava; Sr: Shirakuchidake lava; Tn: Tenbodai lava; and Yb: Mimaya-Yubiyama lava. TL ages are also shown with open circles (Okuno et al. 2013; Sakaguchi et al. 2015).

https://doi.org/10.1017/RDC.2016.66 Published online by Cambridge University Press

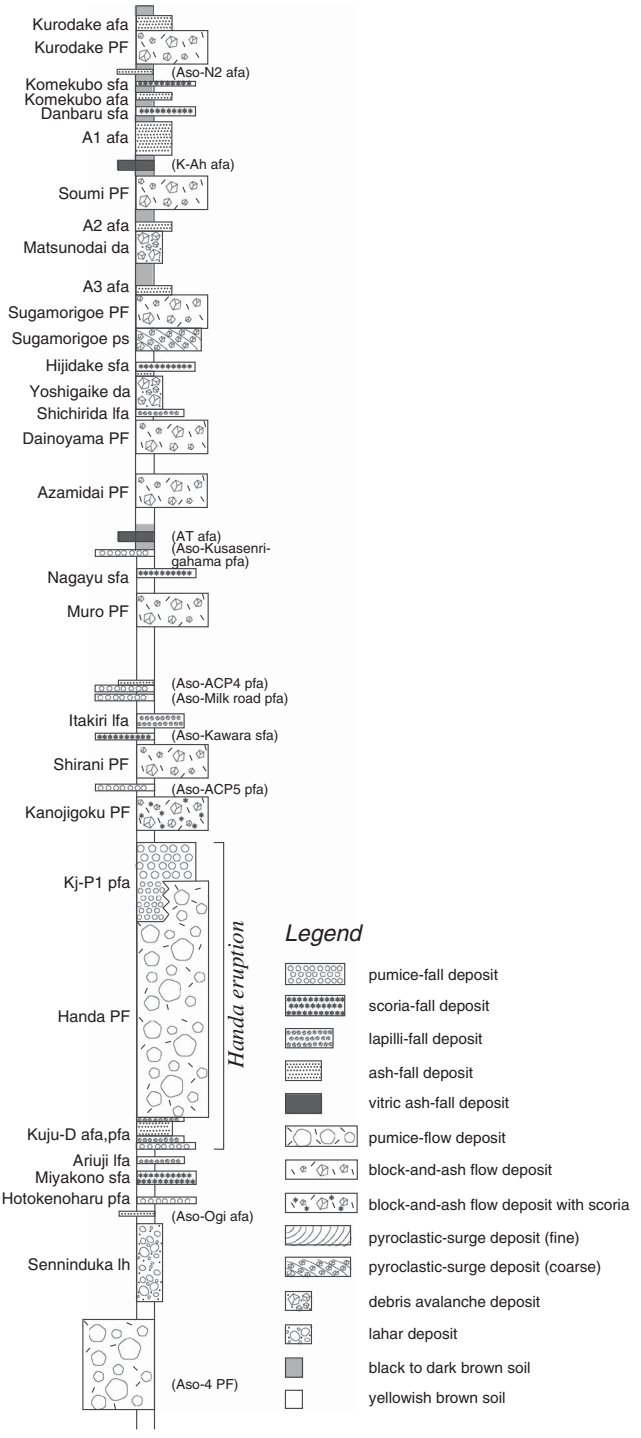

Figure 2 Columnar section of the tephra layers in the Kuju volcanic group (modified from Nagaoka and Okuno 2014). Not to scale. Pfa: pumice-fall deposit; sfa: scoria-fall deposit; lfa: lapilli-fall deposit; afa: ash-fall deposit; PF: pyroclastic-flow deposit; ps: pyroclastic-surge deposit; da: debris avalanche deposit; and lh: lahar deposit. Ages of Aso-4, AT, and K-Ah are 89 ka, 30 cal ka BP, and 7.3 cal ka BP, respectively.

https://doi.org/10.1017/RDC.2016.66 Published online by Cambridge University Press

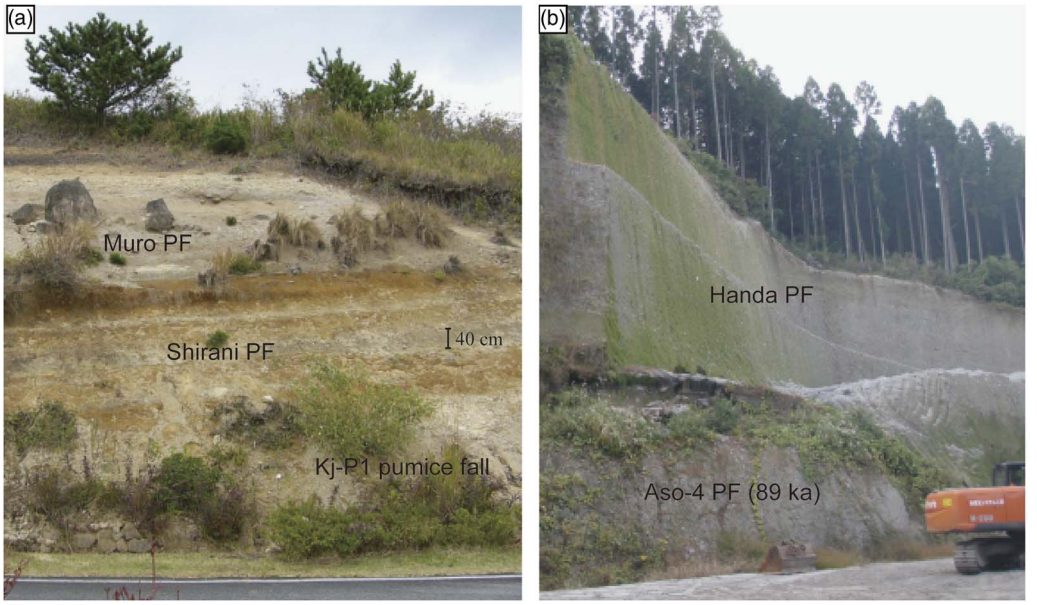

Figure 3 Photographs showing the Handa (Kj-Hd), Shirani (Kj-Sh), and Muro (Kj-Mr) PF deposits: (a) Location A; (b) Location B

of a small-scale caldera. After the Handa eruption, hornblende-andesitic lava domes emerged in the summit area, and associated PF deposits (block-and-ash flow type) flowed down to their foot during the post-caldera stage (Figures 1 and 2). We collected charcoal fragments from the Kj-Hd, Shirani PF (Kj-Sh), and Muro PF (Kj-Mr; also named Nakagumi-bokujo) at locations A and B, respectively (Figure 3).

AMS Radiocarbon Dating

The charcoal fragments were cleaned chemically with acid-alkali-acid (AAA) treatment, and combusted to CO_2. The CO_2 produced was purified cryogenically and then converted catalytically to graphite (Kitagawa et al. 1993), and measured by the NEC 15SDH-2 AMS system (JAEA-AMS-TONO) at the Tono Geoscience Center, JAEA (Saito-Kokubu et al. 2015). All three carbon isotopes in both samples and an NIST oxalic acid standard (HOxII) were measured with the system. To estimate the ^{14}C background level, the ^{14}C content of IAEA C1 (marble) was also measured in the same sequence of sample measurements. The ^{14}C age was calculated by subtracting the ^{14}C concentration of the background sample. We corrected for carbon isotopic fractionation using the $^{13}C/^{12}C$ ratio ($\delta^{13}C_{PDB}$) to determine the conventional ^{14}C age. The ^{14}C errors were evaluated by the ^{14}C reproducibility of repeated measurements on standard targets, and errors in ^{14}C background removal calculations. The obtained $^{13}C/^{12}C$ ratios were used. Conventional ^{14}C dates were calibrated to a calendar year timescale using the IntCal13 data set (Reimer et al. 2013) and the computer program CALIB 7.1 (Stuiver and Reimer 1993).

RESULTS AND DISCUSSION

The AMS ^{14}C dates obtained for PF deposits in the group were 53,520 ± 1330 BP (JAT-8267) for Kj-Hd; 48,390 ± 1170 BP (JAT-8269) for Kj-Sh; and 32,970 ± 210 BP (JAT-8266) and 33,950 ± 220 BP (JAT-8268) for Kj-Mr (Table 1). These dates are mostly consistent with their

https://doi.org/10.1017/RDC.2016.66 Published online by Cambridge University Press

Table 1 AMS radiocarbon dates of charcoal fragments for the Handa (Kj-Hd), Shirani (Kj-Sh), and Muro (Kj-Mr) PF deposits.

Loc.	Stratigraphic position	$\delta^{13}C$ (‰)	^{14}C age (BP)	Lab nr	Calibrated age (cal BP, 2σ)	Reference
A	in Kj-Mr	—	31,690 ± 190	—	35,098–36,057	Kawanabe et al. 1997
C		–24.5	31,910 ± 560	NUTA-4283	34,633–37,243	Okuno et al. 1998
A		–25.6	31,500 ± 170	PLD-3480	34,936–35,816	Nagaoka and Okuno 2015
A		–30.4	32,970 ± 210	JAT-8266	36,370–37,878	This study
A		–30.6	33,950 ± 220	JAT-8268	37,808–38,942	This study
A	in Kj-Sh	—	45,690 ± 990	—	47,042–(50,000)	Kawanabe et al. 1997
A		–25.6	41,060 ± 380	PLD-3479	43,785–45,294	Nagaoka and Okuno 2015
A		–26.5	48,580 ± 1170	JAT-8269		This study
B	in Kj-Hd	–25.1	>40,370	NUTA-4627		Okuno et al. 1998
B		–24.7	53,520 ± 1330	JAT-8267		This study

stratigraphic relations and previous dates (Figures 2 and 3). Although the dates for Kj-Hd and Kj-Sh are out of the range of the calibration curve IntCal13, Kj-Mr could be calibrated to 36.5–39 cal kBP (Table 1). Okuno et al. (1998) originally reported AMS ^{14}C dates from locations B and C for eruption age of Kj-Hd. Based on the ^{14}C dates of this study (Table 1), the PF deposit at location C should be correlated with Kj-Mr. Moreover, the dates for Kj-Hd and Kj-Mr allow us to constrain an age of the Kanojigoku PF deposit (Kj-Kn) (Figure 2).

The combination of TL and ^{14}C methods is useful for establishing the eruptive sequence of lava domes and associated PF deposits. TL ages have been reported (Okuno et al. 2013; Sakaguchi et al. 2015; Figure 1c) of ~40–50 ka for the Kutsukakeyama (Kk) and Hossho-kita (HsK) lavas; ~30–40 ka for the Ogigahana-Minami (OgM), Hosshozan (Hs), and Mimata-Gairinzan (MmG) lavas; and ~20–30 ka for the Hizengajo (Hz) and Kujusan (Ks) lavas. These TL ages correspond to the ^{14}C ages for the PF deposits. Therefore, possible sources may be the HsK lava for Kj-Kn; the Kk lava for Kj-Sh; and the OgM, Hs, and MmG lavas for Kj-Mr.

The eruption of Kj-Hd is dated to ~53.5 kBP. This study also revealed that post-caldera volcanism occurred without a significant time interval after caldera formation by the Handa eruption. Regarding pre-caldera volcanism, the TL ages of the Sensuisan (Sn), Ogigahana (Og), and Iwaigo (Iw) lavas have been reported as ~90–60 ka (Okuno et al. 2013; Figure 1c). Therefore, these lava domes formed intermittently before the caldera formation in the central part of the group.

CONCLUSIONS

We obtained four ^{14}C dates for the Kuju volcanic group from measurements performed at JAEA-AMS-TONO. The Kj-Hd tephra was dated to ~53.5 ka BP, while the two block-and-ash flows, Kj-Sh and Kj-Mr, were dated to ~48.6 and 36.5–39 cal ka BP, respectively. These results, along with the previous TL dates, reveal that the post-caldera volcanism occurred without a

https://doi.org/10.1017/RDC.2016.66 Published online by Cambridge University Press

significant time interval following caldera formation. As a result, the caldera depression was ponded by both lava domes and pyroclastic-flow deposits. As demonstrated by this study, the TL and ^{14}C methods are very useful tools for establishing the eruptive sequence of lava domes and associated pyroclastic-flow deposits.

ACKNOWLEDGMENTS

This study was financially supported by a Grant-in-Aid for Scientific Research (nos. 21101002, 22240082) from the Japan Society for the Promotion of Science (JSPS) and the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. AMS ^{14}C dating has conducted by AMS (JAEA-AMS-TONO) under the Common-Use Facility Program of JAEA. We thank anonymous reviewers for constructive comments that improved the manuscript.

REFERENCES

Kamata H, Kobayashi T. 1997. The eruptive rate and history of Kuju volcano in Japan during the past 15,000 years. *Journal of Volcanology and Geothermal Research* 76:163–71.

Kawanabe Y, Hoshizumi H, Itoh J, Kamata H. 1997. Tephra stratigraphy of the Kuju volcano before K-Ah tephra. *Programme and Abstracts the Volcanological Society of Japan 1997*. Volume 2. p 105. In Japanese.

Kawanabe Y, Hoshizumi H, Itoh J, Yamasaki S. 2015. Geological map of Kuju Volcano. *Geological Map of Volcanoes*, no. 19. Geological Survey of Japan, AIST. In Japanese with English abstract.

Kitagawa H, Masuzawa T, Nakamura T, Matsumoto E. 1993. A batch preparation method for graphite targets with low background for AMS ^{14}C measurements. *Radiocarbon* 35(2):295–300.

Nagaoka S, Okuno M. 2014. Tephra-stratigraphy of Kuju volcano in southwestern Japan. *Earth Monthly (Gekkan Chikyu)* 36(8):281–96. In Japanese.

Nagaoka S, Okuno M. 2015. Eruptive history of Kuju volcanic group, SW Japan. *Transaction of Japanese Geomorphological Union* 36(3):141–58. In Japanese with English abstract.

Newhall CG, Self S. 1982. The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism. *Journal of Geophysical Research* 87(C2):1231–8.

Ohta T. 1991. The evolutional history of the eastern and the central area of Kuju volcano group. *Journal of Petrology, Mineralogy and Economic Geology* 86:243–63. In Japanese with English abstract.

Okuno M, Nakamura T, Kamata H, Ono K, Hoshizumi H. 1998. AMS ^{14}C age of the Handa pyroclastic-flow deposit from Kuju volcano, Japan. *Bulletin of Volcanological Society of Japan* 43(2): 75–9. In Japanese.

Okuno M, Takashima I, Nagaoka S, Aizawa J, Inenaga K, Imazato H, Obuchi S, Fukimoto S, Kaneda H, Kobayashi T. 2013. Thermoluminescence dates for the middle and western parts of Kuju volcano, Kyushu, SW Japan. *Earth Monthly (Gekkan Chikyu)* 62:32–6. In Japanese.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–87.

Saito-Kokubu Y, Matsubara A, Miyake M, Nishizawa A, Ohwaki Y, Nishio T, Sanada K, Hanaki T. 2015. Progress on multi-nuclide AMS of JAEA-AMS-TONO. *Nuclear Instruments and Methods in Physics Research B* 361:48–53.

Sakaguchi T, Yuhara M, Yamasaki K, Takashima I, Okuno M. 2015. Thermoluminesence age and whole-rock chemical compositions of Kami-Yuzawa, Shimo-Yuzawa and Mimata-Gairinzan lavas and Matsunodai debris avalanche deposit, Kuju volcanic group, central Kyushu, Japan. *Fukuoka University Science Reports* 45(2):47–62. In Japanese with English abstract.

Stuiver M, Reimer PJ. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35(1):215–30.