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Volcanic activity of the Satsuma-Iwojima area during the past 6500 years

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Satsuma-Iwojima is a small volcano island located on the northern rim of Kikai caldera to the south of Kyushu, southwest Japan. Observations of new outcrops and ^{14}C dating of the tephra layers have revealed post-caldera activity in the Satsuma-Iwojima area. After the large-scale ignimbrite eruption in 6500 y.B.P., volcanic activity was resumed with rhyolitic activity. At the foot of Iwodake, post-caldera tephra layers are divided into eight units by the development of humic soils. K-In-1 and -2 were formed by basaltic activity with phreatomagmatic eruption around 3900 y.B.P. and had ended by 2200 y.B.P. Other tephra layers (K-Sk-l and K-Sk-u) are rhyolitic ejecta with an increasing proportion of silicified fragments in the younger tephras. On the slope of Iwodake, there are also some pumice fall deposits and pyroclastic flow deposits (K-Iw). From the ^{14}C data of K-Iw, the most recent magmatic activity of Iwodake was around 600–500 y.B.P.

1. Introduction

Satsuma-Iwojima is a small volcanic island located to the south of Kyushu (Fig. 1). Along with Takeshima, is located on the northern rim of the submerged Kikai caldera (Matumoto, 1943). A post-caldera cone, Iwodake, on Satsuma-Iwojima is famous for its high-temperature fumaroles (Shinohara *et al.*, 1993). The most recent eruption of the Satsuma-Iwojima area is an eruption in 1934 which formed a new rhyolitic island, Showa-Iwojima. In recent years, small ash emissions occur from the summit crater of Iwodake, but the ash is composed of silicified rock fragments and there is no sign of essential materials.

The geology and eruptive history of Satsuma-Iwojima area is well described in the Geological map "Satsuma Iojima district" published by Geological Survey of Japan (Ono *et al.*, 1982). In recent years, several new tephra outcrops were exposed on the island and new ^{14}C dating data reveals more detailed eruptive history of the volcano over the past 6500 years, which is described in this paper.

2. Description of Geology

2.1 Geology prior to 6500 years ago

The Kikai caldera was formed by at least three large-scale eruptions with pyroclastic flows (erupted volume >100 km^3) (Fig. 2). The most recent large-scale ignimbrite eruption formed the Takeshima pyroclastic flow deposit, which occurred around 6500 y.B.P. (Ono *et al.*, 1982; Kitagawa *et al.*, 1995). Thus, the geological units of the Satsuma-Iwojima are broadly divided into pre-Takeshima volcanics and post-Takeshima volcanics.

Between the Koabiyama pyroclastic flow and the Takeshima pyroclastic flow, air-fall tephra can now be seen in the sea cliffs near Heikenojo, on the northern end of Satsuma-Iwojima. These new outcrops (Fig. 3) show that this tephra is mainly composed of dark gray andesitic to dacitic lapilli and brown soil with several thin layers of pumice and light-colored fine ash. The air-fall deposits are not altered by hydrothermal activity, and correlate with the Kikai-Komoriko tephra group (K-Km; Okuno *et al.*, 1994) that is exposed on Takeshima. One pumice layer in K-Km on Takeshima island can be correlated with the pumice from the Sakurajima-Satsuma tephra (Sz-S) and ^{14}C data were obtained from soil sample above the pumice (9670–9310 y.B.P.; Okuno *et al.*, 1994). Many EW-striking fissures can be observed in the K-Km at Heikenojo (Fig. 3). The fissures show mainly normal movement or are open cracks, and cut the Takeshima pyroclastic flow, but do not cut into post-Takeshima volcanics. The strikes of the fissures are almost similar to those of the caldera rim. From these observations, it seems that the faulting occurred at just after the Takeshima pyroclastic flow erupted, and may have been related to caldera formation.

2.2 Geology and volcanic activity since 6500 y.B.P.

After the Takeshima pyroclastic flow eruption and caldera formation, two post-caldera volcanoes, Iwodake and Inamuradake, erupted in the northern part of the caldera, and the ejected pyroclastic materials began to cover the all of the Satsuma-Iwojima. Magma compositions of each cones are different. Iwodake erupts rhyolitic magma and Inamuradake erupts basaltic magma. The pyroclastic deposits consist of fine ash with rhyolitic pumice from Iwodake whereas basaltic ejecta from Inamuradake. These tephras can be divided into eight units by black- to brown-colored humic soil layers, which indicate periods of inactivity. Two basaltic tephras divide the post-caldera tephra into three groups: the lower rhyolitic Kikai-Sakamoto tephra group (K-Sk-l), basaltic Kikai-Inamuradake tephra group (K-In) and upper rhyolitic Kikai-Sakamoto tephra group (K-Sk-u). K-Sk-l has two tephras and K-Sk-u has four tephras. Thus, we de-

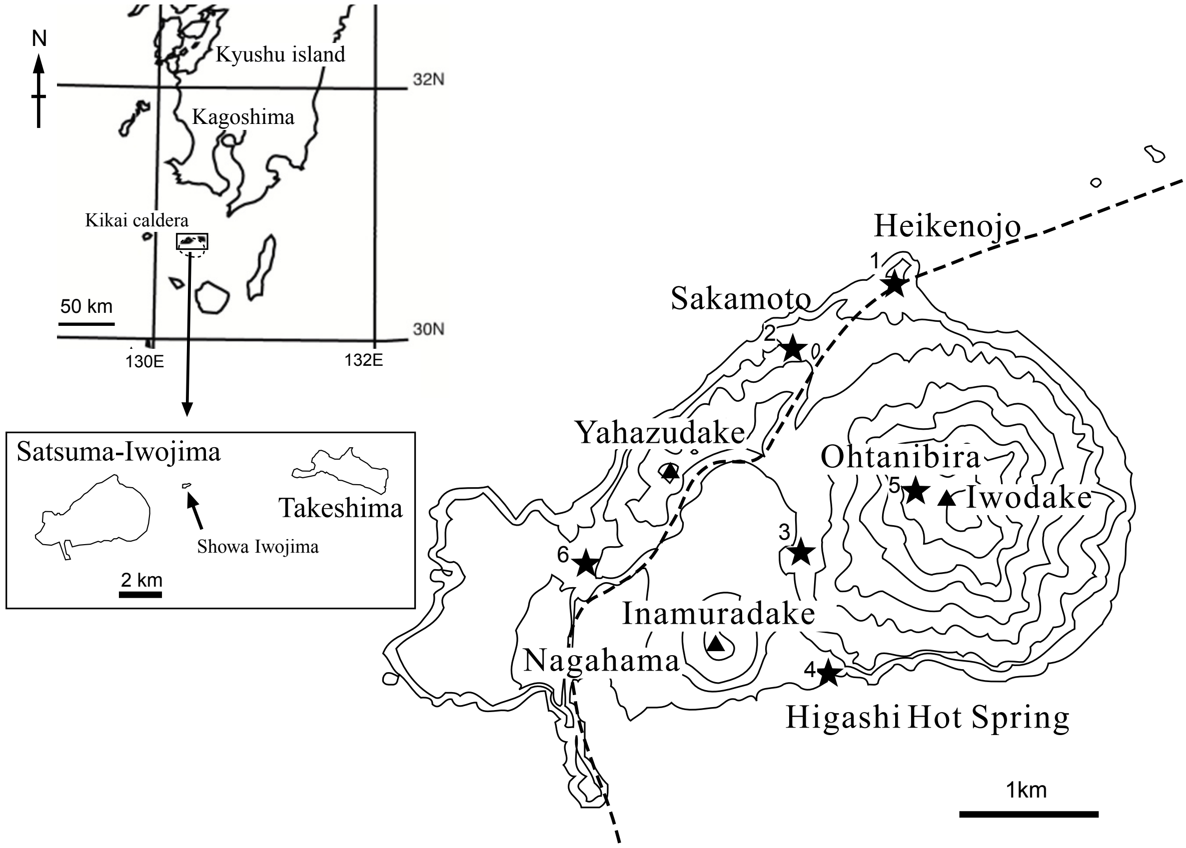

Fig. 1. Location map of Kikai caldera and Satsuma-Iwojima. Broken line indicates caldera rim. Stars with numbers are locality of outcrops.

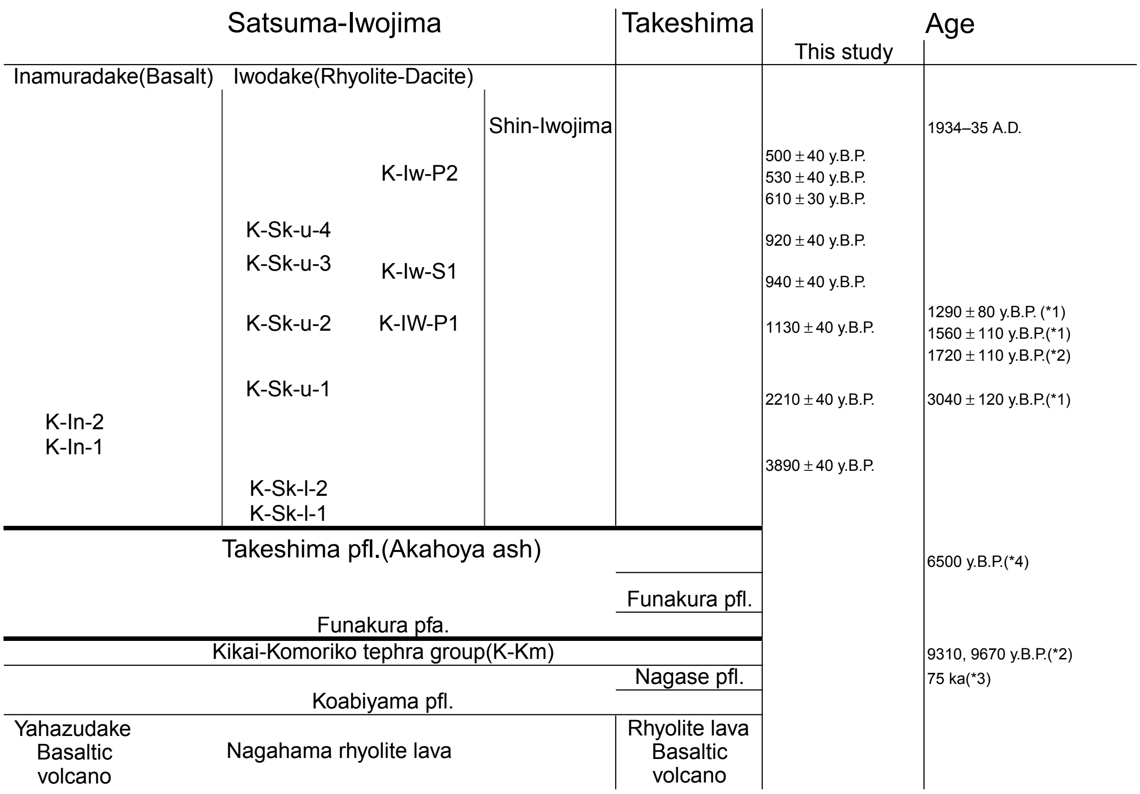

Fig. 2. Geological units in the Kikai area. Names of each unit are after Ono *et al.* (1982). pfl.: pyroclastic flow. pfa.: pumice fall. *1: Ono *et al.* (1982). *2: Okuno *et al.* (1994). *3: Machida and Arai (1992). *4: Kitagawa *et al.* (1995).

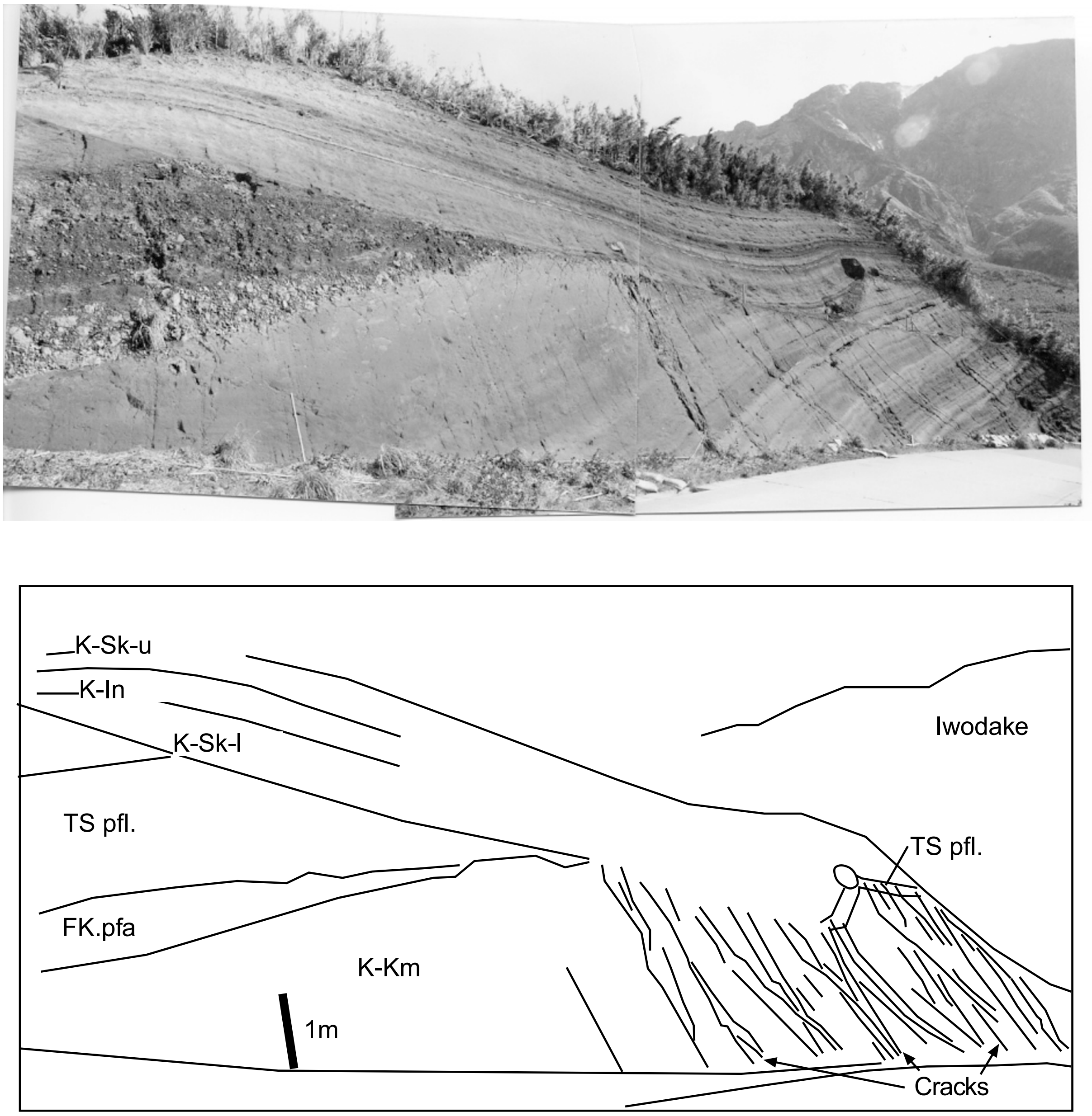

Fig. 3. Outcrop at Heikenojo. The height of the outcrop is about 6 m. K-Km:Kikai-Komoriko tephra group (Okuno *et al.*, 1994). FK.pfa.: Funakura pumice fall. TS pfl.: Takeshima pyroclastic flow (Ono *et al.*, 1982). K-Sk-l: Lower Kikai-Sakamoto tephra group. K-In: Kikai-Inamuradake tephra group. K-Sk-u:Upper Kikai-Sakamoto tephra group.

scribe these units in three sequences: K-Sk-l-1 and -2, K-In-1 and -2 and K-Sk-u-5 to K-Sk-u-8.

Several rhyolitic tephra layers are present on the slope of Iwodake. These tephras are found only on relatively gently inclined slopes and facies are changed frequently; thus, it is difficult to correlate with K-Sk at present. Therefore, we give these tephras an interim name Kikai-Iwodake tephra group (K-Iw). One lava flow from Iwodake covers the Inamuradake lava flow at the Higashi hot spring, and the present slope of Iwodake is not covered by K-In. Thus, the present surface of Iwodake and K-Iw were constructed after the Inamuradake activity.

2.3 Lower Kikai-Sakamoto tephra group

K-Sk-l-1 and K-Sk-l-2 are composed mainly of gray ash and lapilli of lithic fragments. Humic soil between K-Sk-l-1 and K-Sk-l-2 are poorly developed compared to other humic soils of K-Sk, so ^{14}C dating is not possible. A pumice rich layer can be observed in the lower part of K-Sk-l-1 at Heikenojo. The lithic fragments are rhyolitic and relatively fresh, not silicified.

2.4 Kikai-Inamuradake tephra group

K-In-1 and K-In-2 are characterized by scoria layers erupted from Inamuradake. Inamuradake is a small basaltic stratovolcano. Three lava flows and the inner structure of Inamuradake scoria cone can be observed on the southern coast of Inamuradake.

K-In-1 contains two scoria layers and three cemented fine ash layers. Scoria layers of K-In-1 thicken to the west of Inamuradake.

K-In-2 also contains two scoria layers, which are typically

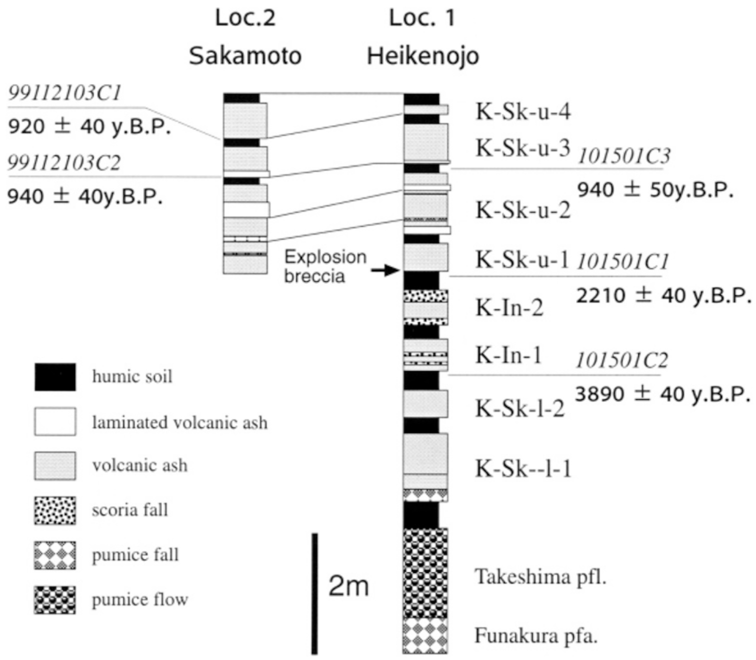

Fig. 4. Columnar sections of K-Sk-l, K-In and K-Sk-u tephra groups. Column numbers are location shown in Fig. 1. Sample numbers, stratigraphical locations and their age are also shown. pfl.: pyroclastic flow. pfa.: pumice fall.

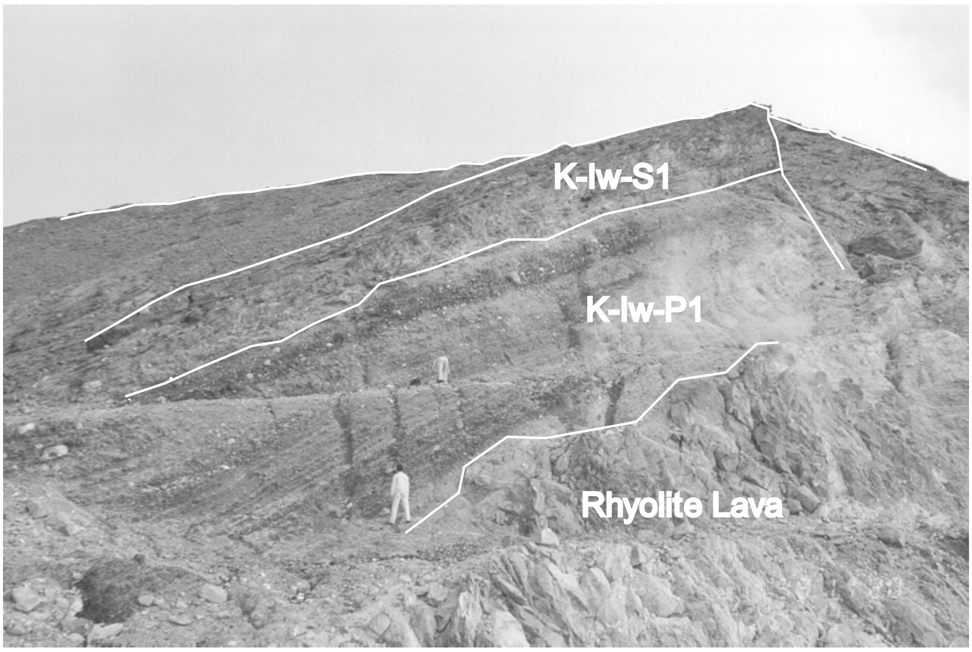

Fig. 5. K-Iw-P1 and K-Iw-S1 at Ohtanibira, southwestern summit of Iwodake. Thick K-Iw-P1 pumice covers the rhyolite lava of Iwodake, and is covered by K-Iw-S1.

relatively thicker than K-In-1. One scoria layer in K-In-2 has 150 cm thick at Location 6 (Fig. 1). At Location 6, K-In-2 contains many thin (1–2 cm) lapilli layers which consist of basaltic lapilli, scoria with chilled margins, ash and crystal fragments. This unit is very hard and displays cross bedding, dune structure and impact structures of ballistic blocks at road side outcrop near Location 6. From the characteristics of the unit and its distribution, this unit originated from a phreatomagmatic eruption near Nagahama during Inamuradake activity. K-In does not contain rhyolitic rock fragments or pumice, thus, Iwodake was probably quiet during the Inamuradake activity.

2.5 Upper Kikai-Sakamoto tephra group

A dark brown-colored humus layer developed on K-In-2, followed by fine ash-dominant units, K-Sk-u-1, K-Sk-u-2, K-Sk-u-3 and K-Sk-u-4. These units do not contain basaltic

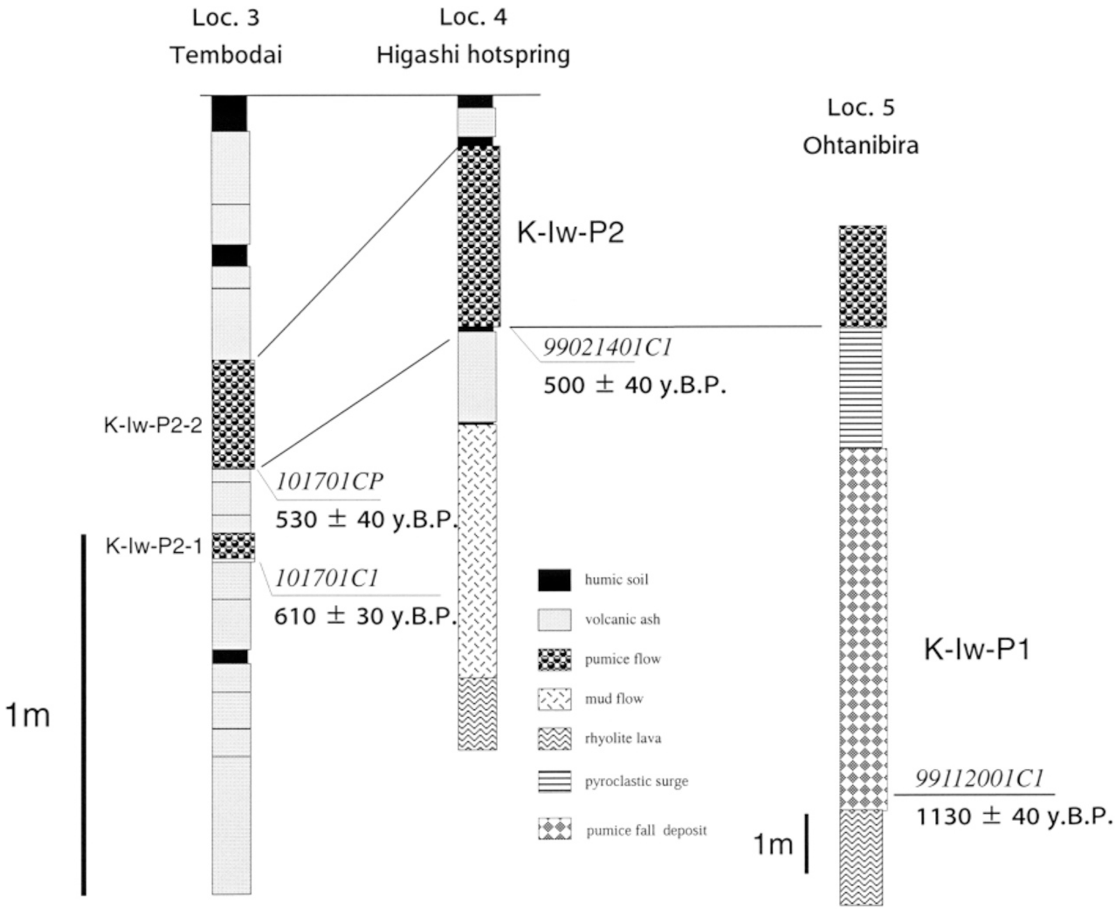

Fig. 6. Columnar section of K-Iw-P2 and K-Iw-P1 tephra. Column numbers are the locations shown in Fig. 1. Scale is different in the column for Location 5. Sample numbers, stratigraphic locations and their ages are also shown.

scoria.

K-Sk-u-1 is a gray, coarse rhyolitic ash layer. Explosion breccia and impact structures are developed at the bottom of K-Sk-u-1, thus, rhyolitic magma activity has resumed with an explosive eruption. The blocks are rhyolite and about 1 m in diameter at maximum. The blocks and lapilli are accessory lithic fragments and some of them are weakly altered. The ballistic blocks occur only from Heikenojo to Sakamoto, so the explosive eruption may have occurred near Iwodake.

K-Sk-u-2 is usually a yellowish-colored ash and characterized by laminated hard ash layer within. The thickness of the laminated ash layer at Location 2 is about 25 cm. This ash layer contains accretionary lapilli and does not contain essential materials such as pumice, thus, it probably formed by phreatic eruptions. The ash layers are thickest near Iwodake, indicating the ash came from phreatic eruptions near Iwodake area. Another thin (<2 cm) fresh white pumice layer also occurs in the lower part of K-Sk-u-2.

K-Sk-u-3 is composed of fine gray ash and a small amount of scattered pumice. Silicified fragments dominate in K-Sk-u-3, which also contain laminated hard ash layer as K-Sk-u-2. The thickness of the laminated ash layer is about 8 cm at Location 2 and it also contains accretionary lapilli.

K-Sk-u-4 is a fine, yellowish-white ash layer and consists mostly of silicified rock fragments. The top of K-Sk-u-4 is covered by humic soil and this suggesting that recent ash emissions have been too small to develop an ash layer.

2.6 K-Iw tephra group

At Ohtanibira, the western area of the summit of Iwodake, a thick (6 m+), partially welded pumice bed (K-Iw-P1) is exposed (Fig. 5). The pumice is composed of well-vesiculated banded pumice, gray pumice and black scoria. The lower and upper parts of K-Iw-P1 are rich in scoria and banded pumice, but the middle part is rich in gray pumice. K-Iw-P1 is covered by a pyroclastic surge deposit (K-Iw-S1) and pumice flow which contain obsidian fragments and breadcrust bombs (K-Iw-P2). The same obsidian and breadcrust bombs are contained in pyroclastic flow deposits on the western slope and at the foot of Iwodake (Fig. 6). K-Iw-P2 at Location 3 is composed of two pyroclastic flow units (upper; K-Iw-P2-2, lower; K-Iw-P2-1) but these units are very similar to each other.

3. ^{14}C Dating

3.1 Samples and method

Two humic soil and seven charcoal samples were collected from K-Sk and K-Iw tephras younger than 6500 y.B.P. ^{14}C dating was done by the Accelerator Mass Spectrometry (AMS) method by BETA ANALYTIC Inc. The $^{13}C/^{12}C$ (δ^{13}CPDB) ratio was also measured and used to correct the isotopic fractionation. ^{14}C ages are converted into

Table 1. AMS ^{14}C dates of K-Sk and K-Iw. Calibration ages are calculated by CALIB (Stuiver and Reimer, 1993), and calibration data are given by Stuiver *et al.* (1998).

Sample No.	Lab. No.	Stratigraphic Position	Material	$\delta^{13}C$ (permil)	^{14}C Age (y.B.P.)	2s maximum caliblation age range (calibration age) minimum calibration age range
99021401C1	Beta-138001	K-Iw-P2-2	Charcoal	−26.7	500 ± 40	cal AD 1331 (1426) 1450
101701CP	Beta-125638	K-Iw-P2-2	Charcoal	−26.8	530 ± 40	cal AD 1320 (1412) 1442
101701C1	Beta-125639	K-Iw-P2-1	Charcoal	−26.7	610 ± 30	cal AD 1296 (1323, 1350, 1390) 1408
99112103C1	Beta-138000	upper soil of K-Sk-u-3	Charcoal	−27.2	920 ± 40	cal AD 1021 (1061, 1086, 1123, 1138, 1156) 1184
99112103C2	Beta-140512	upper soil of K-Sk-u-2	Charcoal	−28.1	940 ± 40	cal AD 1017 (1040, 1100, 1116, 1141, 1151) 1211
101501C3	Beta-125641	upper soil of K-Sk-u-2	Humic soil	−26.1	940 ± 50	cal AD 999 (1040, 1100, 1116, 1141, 1151) 1217
99112001Cl	Beta-137999	K-Iw-P1	Charcoal	−24.6	1130 ± 40	cal AD 780 (897, 922, 942) 998
101501C1	Beta-125636	upper soil of K-In-2	Charcoal	−29.3	2210 ± 40	cal BC 363 (352, 297, 230, 219, 210) 200
101501C2	Beta-125640	upper soil of K-Sk-l-2	Humic soil	−25.1	3890 ± 40	cal BC 2471 (2401, 2378, 2350) 2205

Calibration data from Stuiver *et al.* (1998).

calibrated years by CALIB (Stuiver and Reimer, 1993) with the calibration data set from Stuiver *et al.* (1998). Sample names and ^{14}C dating data are shown in Table 1.

3.2 Results and discussion

Five samples were collected from the K-Sk tephra group at Heikenojo and Sakamoto. Three samples were charred material and the others were humic soil samples.

101501C2, the soil sample below K-In-1, is 3890 ± 40 y.B.P. Thus, the eruption of Inamuradake began around 3900 y.B.P. The charcoal sample (10150C1) between K-In-2 and K-Sk-u-1 is 2210 ± 40 y.B.P. Ono *et al.* (1982) reported the age of the upper soil of Inamuradake scoria is 3040 ± 120 y.B.P. by the β-ray counting method for ^{14}C dating. The difference between Ono *et al.* (1982) and this study may come from the difference of sample type and/or dating method. Although some uncertainty still remains, these dates suggest that basaltic activity stopped and the rhyolitic eruption of Iwodake resumed around 3000–2200 y.B.P.

Three samples were collected from the upper soil of K-Sk-u-2 (soil, 101501C3 and charcoal, 99122103C2) and K-Sk-u-3 (charcoal, 99112103C1). These samples all have an age of about 920–940 y.B.P. Considering that well-silicified ash appears in K-Sk-u-3 and is dominant in K-Sk-u-4, intense fumarolic activity must have began about 950 y.B.P.

The remaining four charcoal samples were collected from K-Iw. Charcoal sample (99112001C1) collected from K-Iw-P1 at Ohtanibira is 1130 ± 40 y.B.P. Ono *et al.* (1982) reported ^{14}C dates of pyroclastic flows from the western slope of Iwodake at about 1560–1290 y.B.P. Thin pumice layer can be seen at the westernmost part of Takeshima, 8 km east of Satsuma-Iwojima. Okuno *et al.* (1994) reported the soil just under the pumice is 1720 ± 110 y.B.P. From the ^{14}C data, rhyolitic magma erupted during the range of about 1700 to 1290 y.B.P. K-Iw-P1 and other rhyolitic ejecta are correlated with K-Sk-u-1 or K-Sk-u-2 by age. K-Sk-u-2 contains a thin pumice layer which may correlate with some of the rhyolitic ejecta of K-Iw. However, banded pumice, which is characteristic in K-Iw-P1, cannot be found in K-Sk tephra group. Therefore correlation of K-Iw-P1 remains problematic.

Three charcoal samples collected from K-Iw-P2 deposits at two different outcrops are 610–500 y.B.P. The last magmatic eruption of Iwodake was thought to be about 1290 y.B.P. (Ono *et al.*, 1982). But these new ages indicate that the magmatic eruption of Iwodake lasted until the 14th to 15th centuries. However, there are no known historical records of eruption at this time.

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References

Kitagawa, H., H. Fukuzawa, T. Nakamura, M. Okamura, K. Takemura, A. Hayashida, and Y. Yasuda, AMS ^{14}C dating of varved sediments from Lake Suigetsu, central Japan and atmospheric ^{14}C change during the late Pleistocene, *Radiocarbon*, **37**, 371–378, 1995.

Machida, H. and F. Arai, Atlas of tephra in and around Japan, 276 p., Univ. of Tokyo Press, 1992 (in Japanese).

Matumoto, T., The four gigantic caldera volcanoes of Kyushu, *Jap. Jour. Geol. Geogr.*, **19**, sp.no., 57 p., 1943.

Okuno, M., F. Arai, H. Moriwaki, T. Nakamura, and T. Kobayashi, Radiocarbon age of humic soil from Kikai-Komoriko tephra group on Takeshima island, southwest Japan, *Rep. Fac. Sci. Kagoshima Univ. (Earth Science and Biology)*, **27**, 189–197, 1994 (in Japanese with English abstract).

Ono, K., T. Soya, and T. Hosono, Geology of the Satsuma-Io-jima district, Quadrangle series, scale 1:50000, Geol. Surv. Japan, 80 p., 1982 (in Japanese with English abstract).

Shinohara, H., W. F. Giggenbach, K. Kazahaya, and J. W. Hedenquist, Geochemistry of volcanic gases and hot springs of Satsuma-Iwojima, Japan: Following Matsuo, *Geochem. J.*, **27**, 271–285, 1993.

Stuiver, M. and P. J. Reimer, Extended ^{14}C database and revised CALIB radiocarbon calibration program, *Radiocarbon*, **35**, 215–230, 1993.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, F. G. McCormac, J. Plicht, and M. Spurk, INTCAL98 Radiocarbon age calibration 24,000—0 cal BP., *Radiocarbon*, **40**, 1041–1083, 1998.

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