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The 18–19 ka Andesitic Explosive Eruption at Usu Volcano, Hokkaido, Japan

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Mount Usu is a Quaternary composite volcano located in southwestern Hokkaido, Japan. Here we report on an andesitic pyroclastic fall deposit (the Usu-Kaminagawa [Us-Ka] tephra) erupted during the initial stage of activity at Usu Volcano. The tephra extends from the volcano to the east, and comprises a lower andesitic pumice-fall deposit and an upper ash-fall deposit. The tephra overlies the Nj-Os tephra, which was erupted from the Nakajima Islands, and is overlain by the Usu Somma Lava, which was extruded during the early stages of activity at Usu Volcano. Radiocarbon dating of buried soils located immediately beneath the Us-Ka tephra yields ages of 18–19 cal ka BP. The distribution, stratigraphy, and lithology of the tephra, and the radiocarbon ages of the buried soils beneath the tephra, suggest that an andesitic explosive eruption occurred at Usu Volcano at *ca.* 18–19 ka. This eruption was probably an early manifestation of activity at Usu Volcano.

Key words: Usu Volcano, tephra, stratigraphy, radiocarbon dating, early volcanic activity.

1. Introduction

Mount Usu is a Quaternary basaltic to rhyolitic composite volcano located at the southern rim of Toya Caldera in southwestern Hokkaido, Japan (Fig. 1). Mount Usu is one of the most active volcanoes in Japan, and has experienced at least nine major eruptions since AD 1663 (Katsui *et al.*, 1985; Katsui, 1988; Matsumoto and Nakagawa, 2010; Mimatsu, 1962; Minakami *et al.*, 1951; Nakagawa *et al.*, 2005; Oba, 1966; Soya *et al.*, 2007; Tomiya *et al.*, 2010; Ui *et al.*, 2002; Yokoyama *et al.*, 1973). Understanding the eruptive history of this volcano is essential for mitigation of the volcanic hazards in the region.

This paper presents a study of an andesitic pyroclastic fall deposit (the Usu-Kaminagawa [Us-Ka] tephra; Yamagata and Machida, 1996), inferred to have been erupted during the initial stages of activity at Usu Volcano (Kobayashi and Miyabuchi, 2006). Published geological and geochronological data for the tephra are sparse (Kobayashi and Miyabuchi, 2006; Machida and Yamagata, 1996; Yamagata and Machida, 1996), and further detailed study of the tephra may provide invaluable information with which to constrain the eruptive history of the volcano. Herein, we describe the distribution, stratigraphy, lithology, and radiocarbon ages of the tephra and discuss the early volcanic history of Usu Volcano.

2. Usu Volcano

Usu Volcano rises to an elevation 733 m above sea level, and is a post-caldera cone of Toya Caldera (Fig. 1). The caldera is 10 km × 11 km in size and formed by violent explosive eruptions associated with pyroclastic flows at *ca.* 110 ka (Ganzawa *et al.*, 2007; Machida and Arai, 2003; Okumura and Sangawa, 1984; Takashima *et al.*, 1992; Yokoyama *et al.*, 1973). The Nakajima Islands, located in the central part of the caldera, formed by multiple extrusions of dacitic lavas at 40–45 ka (Takashima *et al.*, 1992). After formation of the Nakajima Islands, Usu Volcano became active (Soya *et al.*, 2007).

Usu Volcano is a basaltic stratovolcano with a parasitic scoria cone, and also includes a number of silicic lava domes and cryptodomes (Fig. 2). According to Yokoyama *et al.* (1973) and Soya *et al.* (2007), the stratovolcano was constructed at *ca.* 10–20 ka by repeated extrusion of basaltic lavas (Usu Somma Lava) and scoria (Fig. 2A). A parasitic scoria cone (Donkoroyama) formed on the northeastern foot of the stratovolcano during this stage (Fig. 2B). At *ca.* 7–8 ka, the summit of the stratovolcano largely collapsed, resulting in generation of a debris avalanche that travelled down to the southwestern foot of the volcano. As a result of this collapse, an amphitheater that is 2 km in diameter formed at the summit of the stratovolcano (Fig. 2B). After the summit collapse, Usu Volcano was dormant for several thousand years, and the

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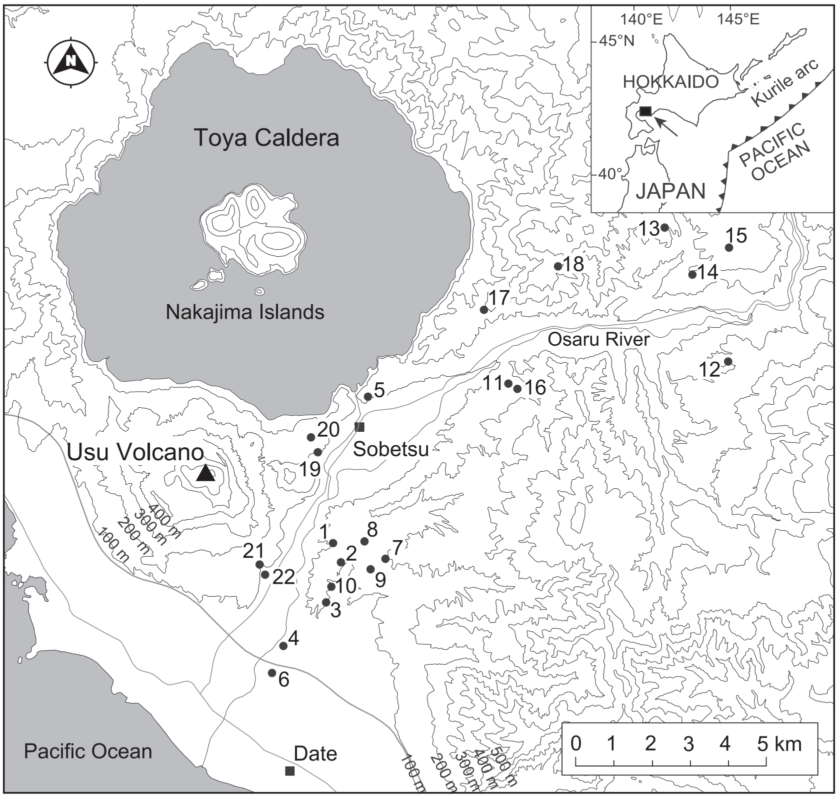

Fig. 1. Location of Usu Volcano, southwestern Hokkaido, Japan. Solid circles mark the survey locations of the Us-Ka tephra. Location numbers of the outcrops correspond to those in Figs 4 and 5. The topographic contour interval is 100 m.

erupted magma changed to a silicic composition. Historical activity commenced with a Plinian eruption in AD 1663. Historical eruptions have been recorded in 1663, 1769, 1822, 1853, 1910, 1943–1945, 1977–1978, and 2000. These historical eruptions formed silicic lava domes and cryptodomes within the summit amphitheater and on the stratovolcano flanks (*e. g*., Ko-Usu, O-Usu, Usu-Shinzan, and Showa-Shinzan; Fig. 2B).

3. Usu-Kaminagawa (Us-Ka) tephra

The Us-Ka tephra is inferred to have been erupted during the initial stages of activity at Usu Volcano, and is distributed to the east of the volcano (Fig. 1) at depths of *ca.* 3–10 m beneath the ground surface. In this paper, the tephra is referred to as the Us-Ka tephra following Yamagata and Machida (1996) and Kobayashi and Miyabuchi (2006). Machida and Yamagata (1996) described the tephra as 'a fallout tephra erupted from Usu Volcano'. The Us-Ka tephra is presently well exposed in a gully at Kami-tateyama in Date City (Loc. 1 in Fig. 1; latitude 42° 31′ 38″N and longitude 140° 52′ 45″E), where the tephra is located *ca.* 3 m beneath the ground surface (Fig. 3A).

At Kami-tateyama (Loc. 1), the Us-Ka tephra comprises a lower pumice-fall deposit (35 cm thick) and an upper ash-fall deposit (20 cm thick) (Fig. 3A). The pumice-fall deposit is gray in color and composed of andesitic pumice clasts (~71 vol.% of the tephra) and accessory lithic pyroclasts (~29 vol.%). The pumice clasts are gray to pale gray, polyhedral with planar surfaces, poorly vesicular (density 1.3–1.5 g/cm^3), and up to 10 cm in size (typically 1–3 cm) (Fig. 3B). The pumice consists of porphyritic andesite containing phenocrysts of plagioclase (< 2 mm long), hornblende (< 2 mm), hypersthene (< 0.5 mm), augite (< 0.5 mm), and opaque minerals (< 0.3 mm) (Table 1). The groundmass has a hyalopilitic texture and consists of fresh volcanic glass and acicular plagioclase crystals (< 0.1 mm). Table 2 lists the whole-rock major element compositions of the pumice (sample numbers UKN-1-2A, -14, and -36). The pumice has SiO_2 contents of 61–62 wt.%. The accessory lithic pyroclasts are angular to subangular (up to 10 cm in size) and comprise various types of andesite. The andesites are gray to brownish gray in color and vary in their oxidation state (non-oxidized to intensely oxidized) and alteration (fresh to intensely altered). The pumice-fall deposit grades upwards to the

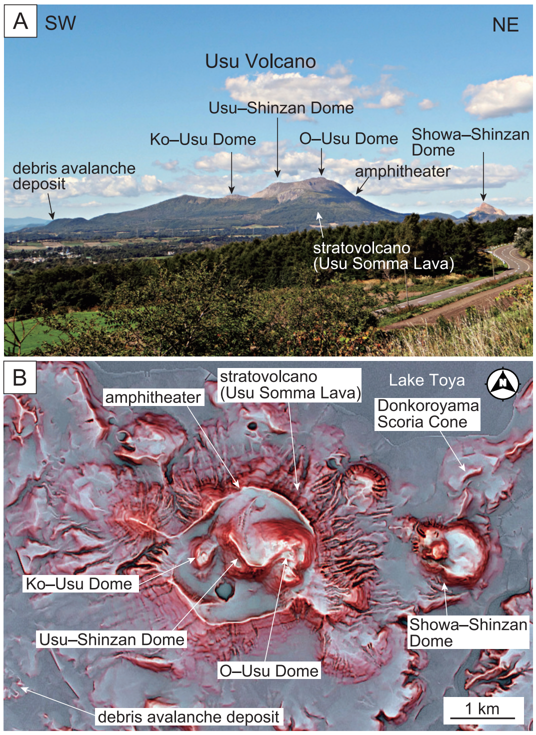

Fig. 2. (A) View of Usu Volcano from the southeast. The volcano comprises a basaltic stratovolcano (Usu Somma Lava) and numerous silicic lava domes and cryptodomes (Ko-Usu, O-Usu, Showa-Shinzan, and Usu-Shinzan domes). (B) Three-dimensional topographic image of Usu Volcano showing its main geological features. The stratovolcano has an amphitheater near its summit. The base map was taken from the Red Relief Image Map (Chiba *et al*., 2007) RRIM10 of Asia Air Survey, using 10 m DEM data of the Geospatial Information Authority of Japan (GSI).

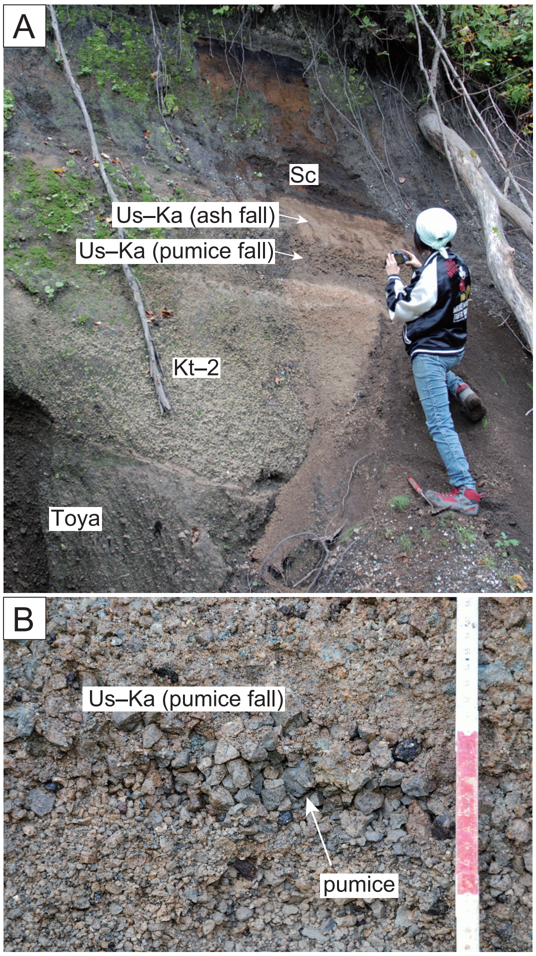

Fig. 3. Photographs of the Us-Ka tephra at Kami-tateyama (Loc. 1 in Fig. 1). (A) Tephra sequence of the Toya pyroclastic flow deposit (Toya), Kt-2 tephra (Kt-2), Us-Ka tephra (Us-Ka), and a scoria-fall deposit (Sc). The Us-Ka tephra comprises a lower pumice-fall and upper ash-fall deposits. (B) Close-up image of the pumice-fall deposit of the Us-Ka tephra, which comprises andesitic pumice and accessory lithic pyroclasts. The red segment of the scale ruler is 10 cm in length.

ash-fall deposit. The ash-fall deposit is brownish gray in color, massive (non-laminated), and comprises lithic fragments, mineral fragments (plagioclase, quartz, hypersthene, hornblende, augite, and opaque minerals), and volcanic glass, which are all up to 0.5 mm in size.

4. Tephra stratigraphy

Stratigraphic sections at representative locations, where the Us-Ka tephra is exposed, are described below. The mineral assemblages and volcanic glass refractive indices of the tephras are listed in Table 1, and their whole-rock major element compositions are presented in Table 2.

4–1 Kami-tateyama (Loc. 1)

The stratigraphic section at Kami-tateyama (Loc. 1 in Fig. 1; Figs 3 and 4A) consists of a tephra sequence comprising the following units (from base to top): (1) the Toya pyroclastic flow deposit (Machida and Arai, 2003); (2) the Kt-2 tephra (Yamagata, 1994); (3) the Us-Ka tephra; (4) a scoria-fall deposit ('a scoria deposit erupted from Usu Volcano'; Machida and Yamagata, 1996); (5) the B-Tm tephra (Machida and Arai, 2003); (6) the Ko-d tephra (Machida and Arai, 2003); and (7) the Us-b tephra (Yokoyama *et al*., 1973).

The Toya pyroclastic flow deposit (>200 cm thick) is pale reddish gray in color, and consists of subrounded, highly vesicular pumice clasts (<12 cm in size) set in a

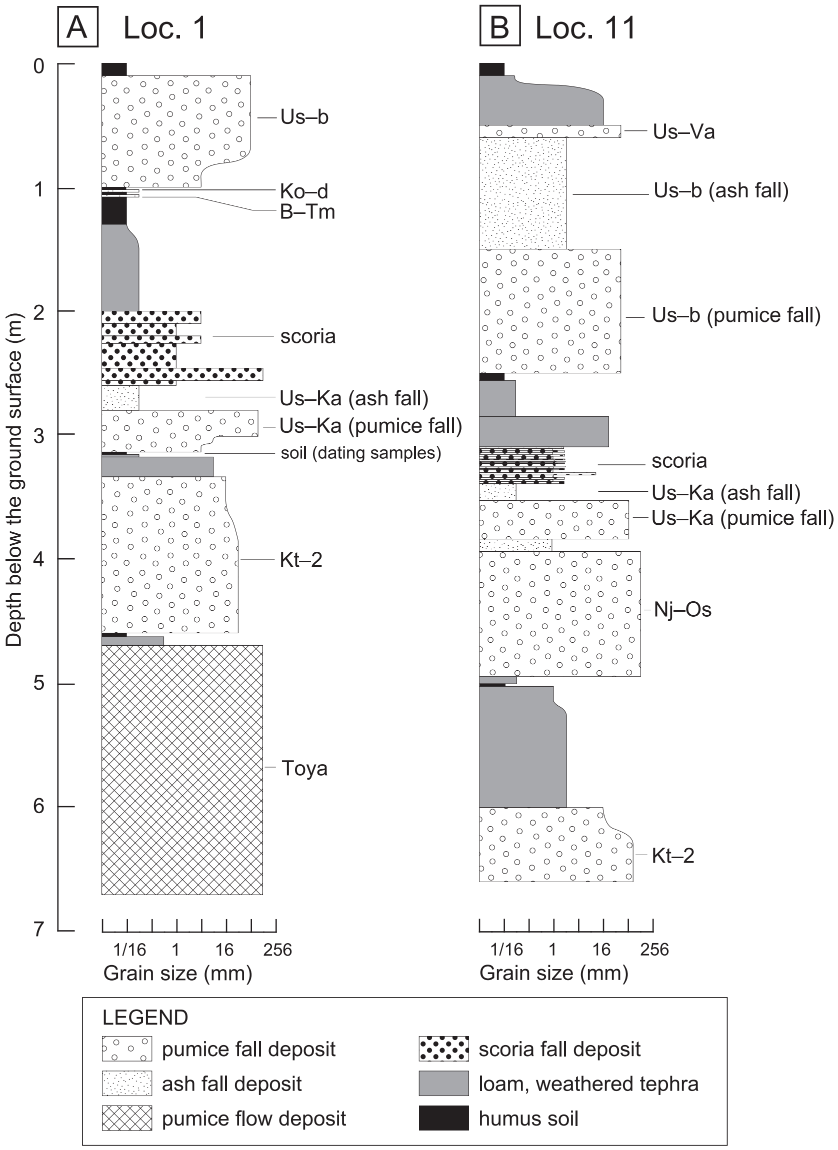

Fig. 4. Stratigraphic sections of the Us-Ka tephra at Kami-tateyama (A; Loc. 1 in Fig. 1) and Nuppa-omanai River (B; Loc. 11). Also shown in (A) is the stratigraphic position of the buried soil samples collected for radiocarbon dating. The Us-Ka tephra lies above the Kt-2 tephra and is covered by the scoria-fall deposit. Note that the Us-Ka tephra is found above the Nj-Os tephra in (B).

fine-grained matrix (Fig. 3A). The pumice consists of fresh volcanic glass and crystals of plagioclase, quartz, hypersthene, hornblende, minor augite, and opaque minerals (Table 1). The deposit grades upwards into its weathered equivalent (5 cm thick), which is capped by a 1-cm-thick dark brown humus soil layer.

The Kt-2 tephra (130 cm thick) is pale yellowish gray, and composed of highly vesicular pumice clasts up to 3 cm in size (Fig. 3A). The pumice consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, and opaque minerals (Table 1). This tephra grades upwards into its weathered equivalent (15 cm thick), which is covered by a pale gray loam layer (1–2 cm thick; the term 'loam' is used for a humus-poor volcanic soil composed of a mixture of weathered tephra, clay, silt, sand, and organic matter; Bates and Jackson, 1983). The pale gray loam layer is partly overlain by a dark brown humus soil layer that is up to 0.5 cm thick.

Table 1. Mineral assemblages and refractive indices of volcanic glass in the tephra deposits. The mineral assemblage of the Usu Somma Lava is also shown.

Name	Mineral assemblage	Refractive index range of volcanic glass	mean	mode
Loc. 1 (Kami-tateyama)				
Us–b tephra (pumice fall deposit)	Pl, Opx, Opq	1.4894–1.4932	1.4909	1.492
Ko–d tephra	Pl, Opx, Cpx, Hb, Opq	1.4942–1.4975	1.4959	1.496
B–Tm tephra	Af, Pl, Qz, Opx, Hb, Cpx, (Bt), Opq	1.5091–1.5119, 1.5184–1.5243	1.5103, 1.5213	1.510, 1.521
Scoria fall deposit	Pl, Opx, Cpx, (Ol), Opq	n.d.	n.d.	n.d.
Us–Ka tephra (ash fall deposit)	Pl, Qz, Opx, Hb, Cpx, Opq	1.4935–1.5024, 1.5042–1.5119	1.4971, 1.5069	1.496
Us–Ka tephra (pumice fall deposit)	Pl, Hb, Opx, Cpx, Opq	n.d.	n.d.	n.d.
Kt–2 tephra	Pl, Opx, Cpx, Opq	1.5137–1.5159	1.5148	1.515
Toya pyroclastic flow deposit	Pl, Qz, Opx, Hb, (Cpx), Opq	1.4960–1.5010	1.4979	1.498
Loc. 11 (Nuppa-omanai River)				
Us–Va tephra	Pl, Qz, Opx, Hb, (Cpx), Opq	1.4988–1.4925	1.4909	1.491
Us–b tephra (ash fall deposit)	Pl, Qz, Opx, Cpx, Opq	1.4954–1.5090	1.4993	1.496
Us–b tephra (pumice fall deposit)	Pl, Qz, Hb, Opx, Opq	1.4898–1.4929	1.4910	1.491
Scoria fall deposit	Pl, Opx, Cpx, Opq	n.d.	n.d.	n.d.
Us–Ka tephra (ash fall deposit)	Pl, Qz, Opx, Hb, Cpx, Opq	n.d.	n.d.	n.d.
Us–Ka tephra (pumice fall deposit)	Pl, Hb, Opx, (Cpx), Opq	n.d.	n.d.	n.d.
Nj–Os tephra	Pl, Qz, Hb, Opx, Opq	1.5017–1.5036	1.5030	1.503
Kt–2 tephra	Pl, Opx, Cpx, Opq	1.5064–1.5088	1.5088	1.508
Loc. 22 (Kami-nagawa)				
Us–b tephra (ash fall deposit)	Pl, Qz, Opx, Cpx, Opq	n.d.	n.d.	n.d.
Usu Somma Lava	Pl, Ol, Cpx, Opx, Opq	n.d.	n.d.	n.d.
Scoria fall deposit	Pl, Opx, Cpx, Opq	n.d.	n.d.	n.d.
Us–Ka (ash fall deposit)	Pl, Qz, Opx, Hb, Cpx, (Bt), Opq	1.4928–1.4980, 1.4998–1.5027	1.4962, 1.5014	1.496, 1.501
Us–Ka (pumice fall deposit)	Pl, Hb, Opx, Cpx, Opq	n.d.	n.d.	n.d.
Nj–Os	Pl, Qz, Hb, Opx, Opq	1.5019–1.5035	1.5029	1.503
Kt–2	Pl, Opx, Cpx, Opq	1.5165–1.5191	1.5177	1.518
Toya pyroclastic flow deposit	Pl, Qz, Opx, Hb, (Cpx), Opq	n.d.	n.d.	n.d.

Pl, plagioclase; Af, alkali feldspar; Qz, quartz; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Hb, hornblende; Bt, biotite; Opq, opaque minerals; n.d., no data. Trace minerals are given in parentheses. The refractive indices of volcanic glass were determined by a RIMS2000 instrument at Kyoto Fission-Track Co. Ltd.

The Us-Ka tephra (55 cm thick) overlies either the loam or soil layer (Fig. 3A) and comprises a lower pumice-fall deposit (35 cm thick) and an upper ash-fall deposit (20 cm thick). The texture and nature of the tephra are described in Section 3. The Us-Ka tephrais directly overlain by the scoria-fall deposit.

The scoria-fall deposit (60 cm thick) is reddish black, well bedded, and comprises basaltic scoria clasts that are up to 12 cm in size (Fig. 3A). At least six fall units (each 2–10 cm thick) are identifiable. The scoria contains crystals of plagioclase, hypersthene, augite, minor olivine, and opaque minerals (Table 1). The scoria has SiO_2 contents of 51–52 wt.% (Table 2; samples UKN-1-9A and -9B). The scoria deposit is overlain by a brown loam layer (70 cm thick), which grades upward into a dark brown humus soil layer (23 cm thick).

The B-Tm tephra (1 cm thick) is pale reddish gray, fine-grained, and composed of volcanic glass and crystals of alkali feldspar, plagioclase, quartz, hypersthene, hornblende, augite, minor biotite, and opaque minerals (Table 1). The B-Tm tephra is overlain by a dark brown humus soil layer that is 3.5 cm thick.

The Ko-d tephra (0.5 cm thick) is pale gray, fine-grained, and composed of volcanic glass and crystals of plagioclase, hypersthene, augite, hornblende, and opaque minerals (Table 1). The Ko-d tephra is covered by a dark brown humus soil layer that is 2 cm thick.

The Us-b tephra (90 cm thick) is pale gray, and composed of moderately vesicular pumice clasts that are up to 6 cm in size. The pumice shows an upward increase in grain size within the tephra layer. The pumice consists of fresh volcanic glass and crystals of plagioclase, hypersthene, and opaque minerals (Table 1). The Us-b tephra is overlain by dark brown surface soil that is 10 cm thick.

4–2 Nuppa-omanai River (Loc. 11)

The stratigraphic section at Nuppa-omanai River (Loc. 11 in Fig. 1; Fig. 4B) consists of a tephra sequence with the following units (from base to top): (1) the Kt-2 tephra; (2) the Nj-Os tephra (Kasugai *et al*., 1990; Machida and Arai, 2003); (3) the Us-Ka tephra; (4) a scoria-fall deposit; (5) the Us-b tephra; and (6) the Us-Va tephra (Yokoyama *et al*., 1973).

The Kt-2 tephra (>60 cm thick) is pale yellowish gray and composed of highly vesicular pumice clasts that are up to 8 cm in size. The pumice consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, and opaque minerals (Table 1). The Kt-2 tephra grades upwards into its weathered equivalent (100 cm thick), which is partially capped by a dark brown humus soil layer (<1 cm thick). The soil layer is covered by a gray loam layer that is 6 cm

Table 2. Whole-rock major element compositions of pumice from the Us-Ka tephra (sample numbers UKN-1-2A, -14, and -36), pumice from the Nj-Os tephra (UKN-11-14A), basaltic scoria from the scoria-fall deposit (UKN-1-9A, -1-9B, and -22-40), and basaltic andesite from the Usu Somma Lava (UGRZ-1).

	Us–Ka tephra			Nj–Os tephra	Scoria fall deposit			Usu Somma
	pumice			pumice	scoria			lava
Sample No.	UKN-1-2A	UKN-1-14	UKN-1-36	UKN-11-14A	UKN-1-9A	UKN-1-9B	UKN-22-40	UGRZ-1
Location No.	1	1	1	11	1	1	22	22
SiO_2 (wt.%)	61.99	61.51	60.51	61.49	51.65	51.44	53.63	54.13
TiO_2	0.61	0.62	0.68	0.67	0.87	0.85	0.95	0.83
Al_2O_3	17.19	17.83	18.01	18.10	18.37	18.68	19.44	17.21
Fe_2O_3*	6.65	6.82	7.27	6.81	11.37	11.16	10.69	11.63
MnO	0.26	0.26	0.26	0.18	0.20	0.19	0.20	0.21
MgO	1.93	1.97	2.21	2.24	4.79	4.46	2.54	4.08
CaO	5.71	5.81	6.16	5.84	9.46	9.43	8.83	8.77
Na_2O	4.17	4.08	4.04	3.29	2.37	2.34	2.47	2.46
K_2O	0.64	0.56	0.53	0.94	0.35	0.39	0.51	0.52
P_2O_5	0.17	0.16	0.16	0.15	0.11	0.10	0.13	0.10
Total	99.33	99.63	99.84	99.72	99.55	99.05	99.40	99.94
L.O.I.	1.05	1.21	0.97	3.00	0.40	0.45	1.57	-0.34

Compositions were determined by X-ray fluorescence spectrometry (Rigaku RIX-2000) at Shimane University, Japan, following the analytical methods described by Kimura and Yamada (1996). $Fe_2O_3^*$＝total iron as Fe_2O_3. L.O.I.＝loss on ignition.

thick.

The Nj-Os tephra (100 cm thick) is pale gray and composed of moderately vesicular pumice clasts that are up to 11 cm in size. The pumice consists of fresh volcanic glass and crystals of plagioclase, quartz, hornblende, hypersthene, and opaque minerals (Table 1). The pumice has SiO_2 contents of 61 wt.% (Table 2; sample UKN-11-14A). The Nj-Os tephra is covered by a brown, weakly laminated, ash-fall deposit that is 10 cm thick, which is interpreted to be a phreatomagmatic fall deposit related to the Nj-Os tephra. The ash-fall deposit is directly overlain by the Us-Ka tephra.

The Us-Ka tephra (44 cm thick) comprises a lower pumice-fall deposit (30 cm thick) and an upper ash-fall deposit (14 cm thick). The pumice-fall deposit is gray and composed of andesitic pumice clasts and accessory lithic pyroclasts. The pumice clasts are gray to pale gray, polyhedral with planar surfaces, poorly vesicular, and up to 7 cm in size (typically 0.5–2.0 cm). The pumice consists of porphyritic andesite, containing phenocrysts of plagioclase, hornblende, hypersthene, minor augite, and opaque minerals (Table 1). The accessory lithic pyroclasts are subangular and composed of various andesite types (＜9 cm in size) and minor granites (＜4 cm in size). The pumice-fall deposit grades upwards to the ash-fall deposit. The ash-fall deposit is brownish gray, weakly laminated, and composed of lithic fragments, mineral fragments (plagioclase, quartz, hypersthene, hornblende, augite, and opaque minerals), and volcanic glass, which are all up to 0.5 mm in size. The ash-fall deposit is directly overlain by the scoria-fall deposit.

The scoria-fall deposit (30 cm thick) is reddish black, well bedded, and composed of basaltic scoria clasts that are up to 3 cm in size. At least nine fall units (each 1–5 cm thick) are identifiable. The scoria contains crystals of plagioclase, hypersthene, augite, and opaque minerals (Table 1). The scoria deposit is overlain by a 25-cm-thick, pale yellowish gray, loam layer that contains pumice. This loam layer is in turn covered by a brown loam layer that is 30 cm thick, which is capped by a dark brown humus soil layer that is 5 cm thick.

The Us-b tephra (190 cm thick) comprises a lower pumice-fall deposit (1 m thick) and an upper ash-fall deposit (90 cm thick, Us-b_1; Yokoyama *et al*., 1973). The pumice-fall deposit is pale gray and composed of moderately vesicular pumice clasts that are up to 5 cm in size. The pumice consists of fresh volcanic glass and crystals of plagioclase, quartz, hornblende, hypersthene, and opaque minerals (Table 1). The ash-fall deposit is greenish gray, massive (non-laminated), and composed of lithic fragments, volcanic glass, and crystals of plagioclase, quartz, hypersthene, augite, and opaque minerals, all of which are up to 2 mm in size (Table 1). The ash-fall deposit is directly overlain by the Us-Va tephra.

The Us-Va tephra (4 cm thick) is pale gray, and composed of moderately vesicular pumice clasts that are up to 4 cm in size. The pumice consists of fresh volcanic glass and crystals of plagioclase, quartz, hypersthene, hornblende, minor augite, and opaque minerals (Table 1). The tephra is overlain by a debris deposit (40 cm thick), which is covered by a dark brown surface soil that is 10 cm thick.

4–3 Kami-nagawa (Loc. 22)

The stratigraphic section at Kami-nagawa (Loc. 22 in Fig. 1; Fig. 5) consists of a tephra sequence comprising the following units (from base to top): (1) the Toya pyroclastic flow deposit; (2) the Kt-2 tephra; (3) the Nj-Os tephra; (4)

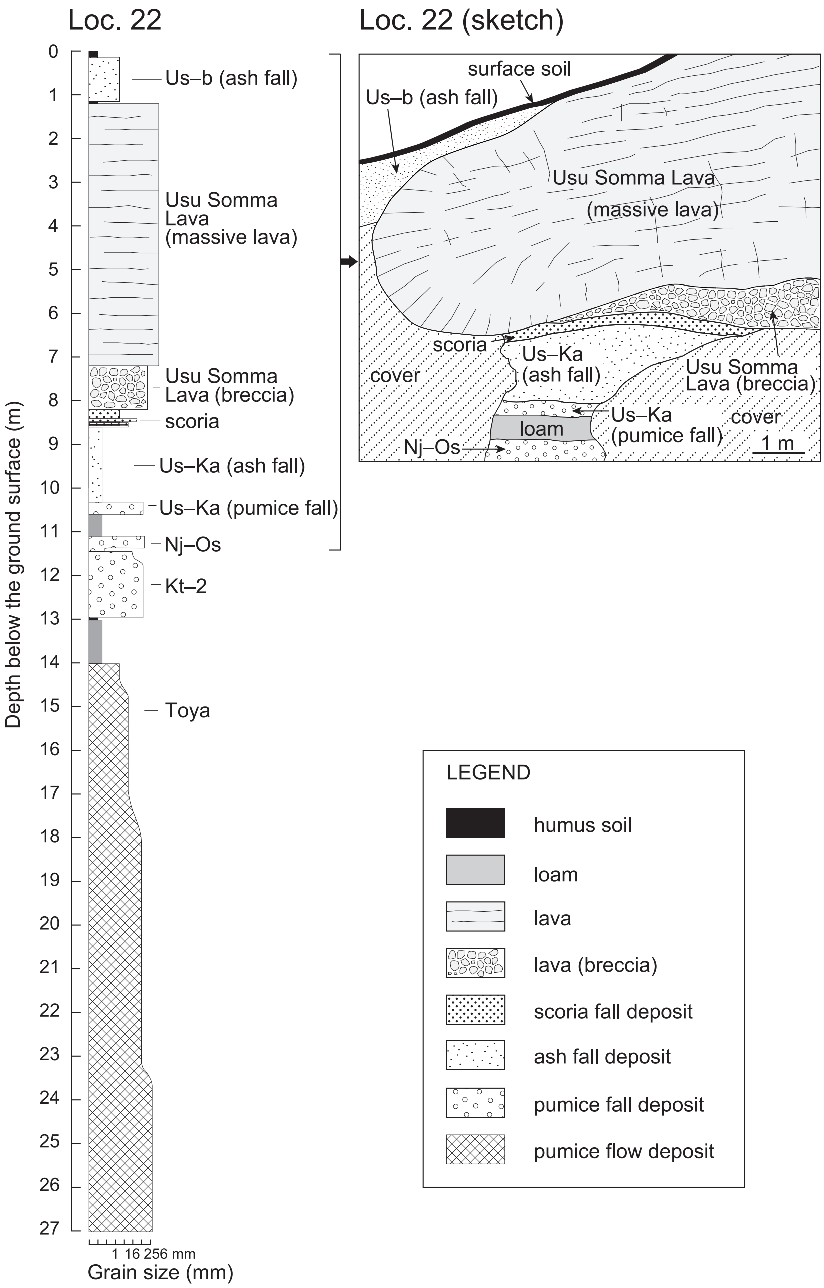

Fig. 5. Stratigraphic section and sketch of the Us-Ka tephra at Kami-nagawa (Loc. 22). The Us-Ka tephra is overlain by a scoria-fall deposit and the Usu Somma Lava.

the Us-Ka tephra; (5) a scoria-fall deposit; (6) the Usu Somma Lava (Yokoyama *et al*., 1973); and (7) the Us-b tephra.

The Toya pyroclastic flow deposit (＞13 m thick) is pale reddish gray, and comprises a lower lithic-rich layer (＞4 m thick; lag breccia) and an upper pumice-rich layer (9 m thick). The lithic-rich layer consists of variably altered, subangular andesite clasts that are ＜30 cm in size, along with minor pumice clasts that are ＜5 cm in size set in a fine-grained matrix. The pumice-rich layer consists of subrounded pumice clasts that are ＜6 cm in size and set in a fine-grained matrix. The pumice in both layers consists of fresh volcanic glass and crystals of plagioclase, quartz, hypersthene, hornblende, minor augite, and opaque minerals (Table 1). The pumice-rich layer is covered by a pale reddish gray loam layer (100 cm thick), and capped by a dark brown soil layer that is 2 cm thick.

The Kt-2 tephra (150 cm thick) is pale yellowish gray and composed of highly vesicular pumice clasts that are up to 7 cm in size. The pumice consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, and opaque minerals (Table 1). The Kt-2 tephra is directly overlain by the Nj-Os tephra.

The Nj-Os tephra (35 cm thick) is brownish gray, matrix-supported, and composed of pale gray, pumice clasts that are <4 cm in size, set in a matrix of brownish gray, fine-grained ash. The pumice consists of fresh volcanic glass and crystals of plagioclase, quartz, hornblende, hypersthene, and opaque minerals (Table 1). The tephra is covered by a pale gray loam layer (30–50 cm thick) or a yellowish gray, reworked pyroclastic deposit (50 cm thick).

The Us-Ka tephra (198 cm thick) consists of a lower pumice-fall deposit (28 cm thick) and an upper ash-fall deposit (170 cm thick). The pumice-fall deposit is gray, and composed of andesitic pumice clasts (*ca.* 70 vol.% of the deposit) and accessory lithic pyroclasts (*ca.* 30 vol.%). The pumice clasts are gray to pale gray, polyhedral with planar surfaces, poorly vesicular, and up to 21 cm in size (typically <12 cm). The pumice consists of porphyritic andesite containing phenocrysts of plagioclase, hornblende, hypersthene, augite, and opaque minerals (Table 1). The accessory lithic pyroclasts are subangular and composed of various andesite types (up to 7 cm in size) and minor granites (up to 20 cm in size). The ash-fall deposit grades upwards in color from gray to reddish brown, is weakly laminated, and is composed of lithic fragments, mineral fragments (plagioclase, quartz, hypersthene, hornblende, augite, minor biotite, and opaque minerals), and volcanic glass, which are all up to 0.5 mm in size (Table 1). The deposit contains abundant accretionary lapilli that are <5 mm in size, which suggests it is a phreatomagmatic fall deposit. The ash-fall deposit is directly overlain by the scoria-fall deposit.

The scoria-fall deposit (40 cm thick) is reddish black, well bedded, and composed of basaltic scoria clasts that are up to 3 cm in size. Six fall units (each 2–20 cm thick) are identifiable. The scoria contains crystals of plagioclase, hypersthene, augite, and opaque minerals (Table 1). The scoria has a SiO_2 content of 54 wt.% (Table 2; sample UKN-22-40). The scoria deposit is directly covered by the Usu Somma Lava.

The Usu Somma Lava (6 m thick) comprises a lower breccia facies (1 m thick) and an upper massive lava facies (5 m thick). The breccia is gray, clast-supported, and composed of angular, vesicular basaltic andesite clasts that are 5–20 cm in size. The breccia grades upwards into the massive lava characterized by platy joints with 20–30 cm spacing and columnar joints spaced at 2 m intervals. The massive lava consists of porphyritic basaltic andesite containing phenocrysts of plagioclase, olivine, augite, hypersthene, and opaque minerals (Table 1). The lava has a SiO_2 content of 54 wt.% (Table 2; sample UGRZ-1). The lava is covered by a dark gray, humus soil layer that is 5 cm thick.

The Us-b tephra (100 cm thick, Us-b_1; Yokoyama *et al*., 1973) is greenish gray and comprises lithic fragments, volcanic glass, and crystals of plagioclase, quartz, hypersthene, augite, and opaque minerals, all of which are up to 2 mm in size (Table 1). The tephra is covered by a dark brown surface soil that is 15 cm thick.

5. Distribution and volume of the Us-Ka tephra

The thickness distribution and maximum grain size of the pumice-fall deposit of the Us-Ka tephra are shown in Fig. 6A and 6B, respectively. The maximum grain size was calculated as the average long-axis diameter of the three largest pumice clasts. These data suggest that the pumice-fall deposit increases in thickness and maximum grain size toward Usu Volcano. The deposit was not found on Nakajima Islands within Toya Caldera. The volume of the pumice-fall deposit calculated following the method of Hayakawa (1985) using the 30-cm isopach is $1.8\times10^8\,m^3$.

The ash-fall deposit of the Us-Ka tephra also increases in thickness towards Usu Volcano (*e.g.*, 170 cm at Loc. 22; 20 cm at Loc. 1; 14 cm at Loc. 11). However, the thickness distribution of the deposit is not presented here as the ash-fall deposit is less well preserved than the pumice-fall deposit and, as such, it was difficult to obtain accurate thickness data for the ash-fall deposit.

6. Radiocarbon dating

Radiocarbon ages were determined for five samples of humus soil collected from the entire thickness of the 5-mm-thick soil layer that is found just beneath the pumice-fall deposit of the Us-Ka tephra at Kami-tateyama (Fig. 4A; Table 3; samples UKN-4A, -4B, -23, -24, and -4A-AAA). This soil layer was found when a new gully formed in 2011. The soil layer contains no modern plant roots and shows no field evidence of disturbance (*e.g.*, bioturbation or erosion) during or after deposition. The five samples were collected from the same stratigraphic position. The soil samples are dark brown in color, and are fine-grained organic sediments (grain size <0.5 mm).

Radiocarbon dating of the samples was performed by Beta Analytic (Miami, USA). Four samples (UKN-4A, -4B, -23, and -24) were pretreated by acid washes to remove carbonates. In the pretreatment, each soil sample was: (1) sieved to $<180\,\mu m$; (2) washed with 2N HCl at 80℃ for 4 h; (3) rinsed with hot (>95℃) distilled water; (4) washed with 2N HCl at 80℃ for 4 h; (5) rinsed with hot distilled water; and (6) dried in a oven at 70℃ for 18 h. The remaining carbon representing the bulk organic fraction was analyzed by accelerator mass spectrometry

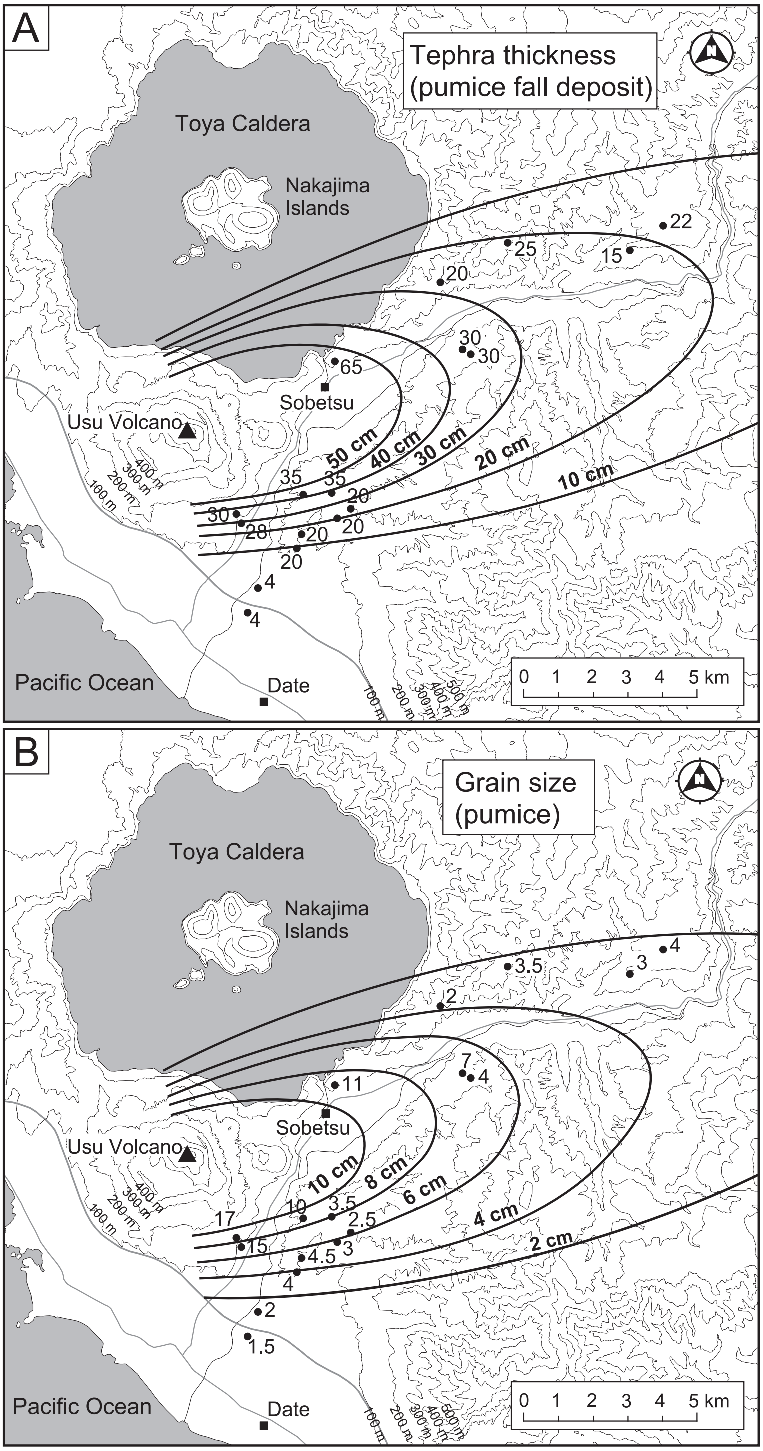

Fig. 6. Thickness distribution (A) and maximum grain size distribution of pumice (B) of the Us-Ka pumice-fall deposit. The maximum grain size was taken to be the average of the long-axis diameter of the three largest pumice clasts. The tephra increases in thickness and maximum grain size towards Usu Volcano.

Table 3. Radiocarbon ages of buried soils collected from the entire thickness of the 5-mm-thick soil layer that is found just beneath the pumice-fall deposit of the Us-Ka tephra at Kami-tateyama (Fig. 4A).

Sample number	Material	Method	^{14}C age* (BP; ±1σ)	δ^{13}C (‰)	Conventional ^{14}C age** (BP; ±1σ)	Laboratory code	Calibrated age*** (cal. BP; 2σ)
UKN-4A	organic sediment (bulk organic fraction)	AMS	15,520 ± 60	–24.6	15,530 ± 60	Beta-288344	18,630–18,810
UKN-4B	organic sediment (bulk organic fraction)	AMS	15,760 ± 60	–24.5	15,770 ± 60	Beta-288345	18,810–18,930
UKN-23	organic sediment (bulk organic fraction)	AMS	14,790 ± 60	–24.0	14,810 ± 60	Beta-288346	17,900–18,050 and 18,350–18,430
UKN-24	organic sediment (bulk organic fraction)	AMS	15,050 ± 60	–24.7	15,050 ± 60	Beta-288347	18,050–18,350 and 18,430–18,540
UKN-4A-AAA	organic sediment (alkali insoluble fraction)	AMS	14,910 ± 60	–24.2	14,920 ± 60	Beta-333269	17,980–18,140 and 18,260–18,490

* Based on Libby's half-life (5568 y) and uncorrected for δ^{13}C values. Ages are expressed in BP (years before AD 1950) with an error range of 1σ. ** Conventional ^{14}C age with a δ^{13}C correction. Ages are expressed in BP with an error range of 1σ. *** Calibrated ages were calculated from the conventional ^{14}C ages using a program developed by Beta Analytic, based on the IntCal09 calibration database (Heaton *et al*., 2009; Oeschger *et al*., 1975; Reimer *et al*., 2009; Stuiver and Braziunas, 1993) with a spline smoothing function for the calibration curve (Talma and Vogel, 1993). Ages are expressed in cal BP with an error range of 2σ (95% probability). AMS = accelerator mass spectrometry.

(AMS). One sample (UKN-4A-AAA) was pretreated by sequential acid-alkali-acid washes to remove carbonates and humic acid. In the pretreatment, the soil sample was: (1) sieved to <180 μm; (2) washed with 0.5N HCl at 80℃ until carbonates were removed; (3) rinsed with hot ($>$ 95℃) distilled water; (4) agitated with 1%-2% NaOH at 25℃; (5) left in 1%-2% NaOH at room temperature for 8 h; (6) rinsed with hot distilled water; (7) processes (4) to (6) were repeated until the supernatant liquid became clear; (8) washed with 0.5N HCl at 80℃ for 1 h; (9) rinsed with hot distilled water; and (10) dried in a oven at 70℃ for 12 h. The remaining alkali-insoluble carbon was analyzed by AMS. δ^{13}C values of all samples were analyzed using a stable isotope mass spectrometer relative to the Vienna Pee Dee Belemnite (VPDB) standard.

The samples yield conventional radiocarbon ages of 15,530 ± 60 (UKN-4A), 15,770 ± 60 (UKN-4B), 14,810 ± 60 (UKN-23), 15,050 ± 60 (UKN-24), and 14,920 ± 60 BP (UKN-4A-AAA) (1σ error; Table 1). The samples pretreated with acid washes (UKN-4A, -4B, -23, and -24) and acid-alkali-acid washes (UKN-4A-AAA) yielded identical ages.

Calibrated ages were calculated from the conventional radiocarbon ages using a program developed by Beta Analytic and based on the IntCal09 calibration database (Heaton *et al*., 2009; Oeschger *et al*., 1975; Reimer *et al*., 2009; Stuiver and Braziunas, 1993) with a spline smoothing function for the calibration curve (Talma and Vogel, 1993). The calibrated ages are 18,630–18,810 (UKN-4A), 18,810–18,930 (UKN-4B), 17,900–18,430 (UKN-23), 18,050–18,540 (UKN-24), and 17,980–18,490 cal BP (UKN-4A-AAA) (2σ error range; 95% probability; Table 1).

7. Discussion

The Us-Ka tephra is inferred to have been erupted from Usu Volcano for the following reasons: (1) the Us-Ka tephra increases in thickness and maximum grain size toward Usu Volcano (Fig. 6); (2) the Us-Ka tephra contains large pumice clasts (up to 21 cm in size) and lithic pyroclasts (up to 20 cm) at Kami-nagawa (Loc. 22), on the southeastern slope of Usu Volcano; and (3) pumice in the Us-Ka tephra is characterized by low K_2O (0.5–0.6 wt.%; Table 2), which is consistent with chemical composition of volcanic products from Usu Volcano (Soya *et al*., 2007). Although the Nakajima Islands within Toya Caldera are located nearby Usu Volcano, we discount the possibility that the Us-Ka tephra was erupted from the Nakajima Islands as: (1) the Us-Ka tephra was not found on the islands; and (2) the Us-Ka tephra has lower K_2O than the Nj-Os tephra (0.9 wt.%; Table 2), which was erupted from the islands (Kasugai *et al*., 1990; Machida and Arai, 2003).

The stratigraphy of the Us-Ka tephra at Nuppa-omanai River (Loc. 11; Fig. 4B) and Kami-nagawa (Loc. 22; Fig. 5) suggests that the Us-Ka tephra occurs above the Nj-Os tephra that was erupted from the Nakajima Islands (Kasugai *et al*., 1990; Machida and Arai, 2003). Therefore, the Us-Ka tephra was erupted after formation of the Nakajima Islands. The stratigraphy of the Us-Ka tephra at Kami-nagawa (Loc. 22; Fig. 5) suggests that the Us-Ka tephra is directly overlain by a scoria-fall deposit and the Usu Somma Lava (Fig. 5), both of which were extruded during the initial stages of activity at Usu Volcano (Soya *et al*., 2007; Yokoyama *et al*., 1973). Thus, we infer that the Us-Ka tephra was produced during the early stages of activity at Usu Volcano. Some studies have already noted that the Us-Ka tephra was produced during the early stages of activity at Usu Volcano (Kobayashi and Miyabuchi, 2006; Machida and Yamagata, 1996; Yamagata and Machida, 1996), which is consistent with our results.

The eruption age of the Us-Ka tephra can be inferred from the radiocarbon ages of buried soils just beneath the tephra (Table 3). In general, radiocarbon ages of buried soils located immediately below a mass flow or pyroclastic deposit represent the emplacement age of the deposit (Okuno *et al.*, 1997; Orlova and Panychev, 1993; Xu *et al.*, 2004). However, this requires that the deposit overlies the soil with no disturbance and that the soil was a closed system after emplacement of the deposit. In the case of the Us-Ka tephra, the soil shows no sign of disturbance, suggesting that the tephra passively mantled the soil layer. Soil samples pretreated by acid washes (UKN-4A, -4B, -23, and -24) and pretreated by acid-alkali-acid washes (UKN-4A-AAA) yield identical ages, indicating that a closed system was maintained in the soil layer after emplacement of the tephra. We therefore infer that radiocarbon ages of the buried soil immediately below the Us-Ka tephra represent the emplacement age of the Us-Ka tephra. Calibrated ages for the samples are 18–19 cal ka BP (Table 1), suggesting that the Us-Ka tephra was emplaced at this time. We therefore conclude that an explosive andesitic eruption responsible for the Us-Ka tephra occurred at *ca*. 18–19 ka at Usu Volcano. This age is consistent with the timing of initiation of activity at Usu Volcano estimated by previous studies (10–20 ka; Yokoyama *et al*., 1973; Soya *et al*., 2007).

The Us-Ka tephra comprises a lower pumice-fall deposit that consists mainly of andesitic pumice, and an upper ash-fall deposit that includes accretionary lapilli, suggesting that the tephra was formed by early, explosive andesitic magmatism and later, phreatomagmatic activity. The presence of phreatomagmatic activity implies a water-rich environment. Such an environment is to be expected because Usu Volcano is located at the southern rim of Toya Caldera, which is filled with water. The eruption that produced the Us-Ka tephra most likely produced a volcanic crater, although we did not locate such a crater in the area of Usu Volcano. The source crater of the Us-Ka tephra may have been buried by emplacement of the Usu Somma Lava (Fig. 2B).

Most previous studies (*e.g*., Katsui *et al.*, 1985; Katsui, 1988; Soya *et al*., 2007; Yokoyama *et al*., 1973) have suggested that the eruptive history of Usu Volcano is characterized by early basaltic activity that produced the Usu Somma Lava ($SiO_2 = 49–54$ wt.%; Yokoyama *et al.*, 1973) and later silicic activity that produced lava domes ($SiO_2 = 68–73$ wt.%; Yokoyama *et al.*, 1973), and that andesitic activity has not taken place at Usu Volcano. However, our study indicates that Usu Volcano began activity with the extrusion of andesitic magma ($SiO_2 = 61–62$ wt.%; Table 2), and this necessitates a revision of the eruptive history of the volcano. The chemical composition of the Us-Ka tephra ($SiO_2 = 61–62$ wt.%) is intermediate to that of the Usu Somma Lava and lava domes and, as such, our study indicates that further detailed petrological study of the Us-Ka tephra would provide invaluable information on the magmatic evolution of Usu Volcano.

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(Editorial handling Noriko Hasebe)

北海道有珠火山，18–19 ka の安山岩質爆発的噴火

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北海道南西部の有珠山東方に分布する有珠上長和テフラ (Us–Ka) は，下部の軽石層と，上部の細粒火山灰層からなる．軽石層は安山岩質の軽石と石質岩片からなり，軽石の SiO_2量は 61–62 wt.% である．火山灰層は火山豆石を含み，マグマ水蒸気噴火により形成されたことを示す．Us–Ka テフラは，洞爺湖中島起源の Nj–Os テフラを覆い，有珠外輪山溶岩に覆われる．テフラ直下の土壌層は，18–19 cal ka BP の放射性炭素年代値を示す．テフラの層厚と最大粒径は有珠山に向かって増大し，有珠山から噴出したことを示す．Us–Ka テフラは，約 18–19 ka の爆発的噴火により形成され，この噴火は有珠火山の先駆的な活動であると考えられる．有珠山は，安山岩質の爆発的噴火により活動を開始し，玄武岩質溶岩（有珠外輪山溶岩）を噴出して成層火山を形成した．この成層火山の山体崩壊後，珪長質マグマの噴出により溶岩ドーム群を形成した．