Article

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A Fallout Tephra from Tenchozan Volcano, Shiretoko Peninsula, Hokkaido, Japan

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Mt. Tenchozan, located on the Shiretoko Peninsula, eastern Hokkaido, Japan, is a Quaternary andesitic volcano with crater chains on its summit. This paper reports on a fallout tephra (the Ten-a tephra) extruded from the volcano. The tephra extends from the summit area of the volcano to the eastern shore of the peninsula, and is composed of pyroclastic lithic fragments, minor juvenile pumice and ash. The tephra increases in thickness and grain size toward the summit of the volcano. Radiocarbon dating of a buried soil located immediately beneath the tephra yields an age of 1930±40 years BP, and a calibrated calendar age of 1960–1810 cal BP (2σ, 95% probability). The distribution, components and radiocarbon age of the tephra suggest that phreatomagmatic eruptions took place at the summit of the volcano at *ca*. 1900 years BP, resulting in the formation of the crater chains.

Key words: fallout tephra, radiocarbon age, crater chain, Tenchozan Volcano, Shiretoko Peninsula

1. Introduction

Mt. Tenchozan is a Quaternary andesitic volcano located on the Shiretoko Peninsula, eastern Hokkaido, Japan (Fig. 1). The volcano has two crater chains on its summit (Fig. 2, Moriya, 1984; Katsui *et al*., 1985). The craters display well-preserved, primary morphological features, suggesting a series of eruptions occurred in recent geological time. However, the timing of the eruptions remains unknown. This paper reports on the distribution, components and radiocarbon age of a fallout tephra extruded from the volcano, and discusses the timing of the crater-forming eruptions.

2. Tenchozan Volcano

Tenchozan Volcano is located 4.5 km southwest of Rausu Volcano (Fig. 2A). It reaches an elevation of 1046 m above sea level and has a base diameter of 2.5×4 km (Fig. 2A). The volcanic edifice is flat-topped with steeply sloping sides and is composed of andesitic lavas (Tenchozan Lavas, Fig. 2). The lavas retain their primary morphological features, including curved flow fronts, and consist mainly of hypersthene–augite andesite. Table 1 lists the whole-rock major-element chemical composition of the andesite (sample numbers Ten-13, -14, -15, -16, -18, -20), which contains 57–61 wt.% SiO_2.

There are two chains of explosion craters on the summit (Fig. 2B, Katsui *et al*., 1985). The northern chain trends southwest–northeast, extends for 1800 m, and consists of 10 explosion craters. Each crater is circular to elliptical in plan view, 100–250 m in diameter, and 30–70 m deep. Some craters are connected to each other. Larger craters are filled with water (Fig. 3A and 3B). The southern chain trends southwest–northeast to west–east, extends for 700 m, and consists of four explosion craters. Each crater is elliptical in plan view, 70–100 m in diameter, and 20–30 m deep. At present, the craters in both chains contain no active fumaroles. Historical records make no mention of volcanic eruptions from these craters.

3. Fallout Tephra extruded from Tenchozan Volcano

3–1 Nomenclature

The newly identified fallout tephra extends from the Tenchozan summit to the eastern shore of the Shiretoko Peninsula. Outcrop locations are shown in Figure 2. In this paper, the tephra is referred to as the 'Tenchozan-a tephra' (Ten-a tephra) (Goto *et al*., 2005; Nakamura *et al*., 2008; Goto, 2009). The type locality is in a gully located 100 m east of Shiretoko Pass (Loc. 1 in Fig. 2, latitude 44°03′17″N, longitude 145°06′24″E), where the tephra is located approximately 30 cm beneath the surface (Fig. 4).

3–2 Description

At the type locality, the Ten-a tephra is a 50 cm thick, pale brown, massive (non-stratified) pyroclastic deposit,

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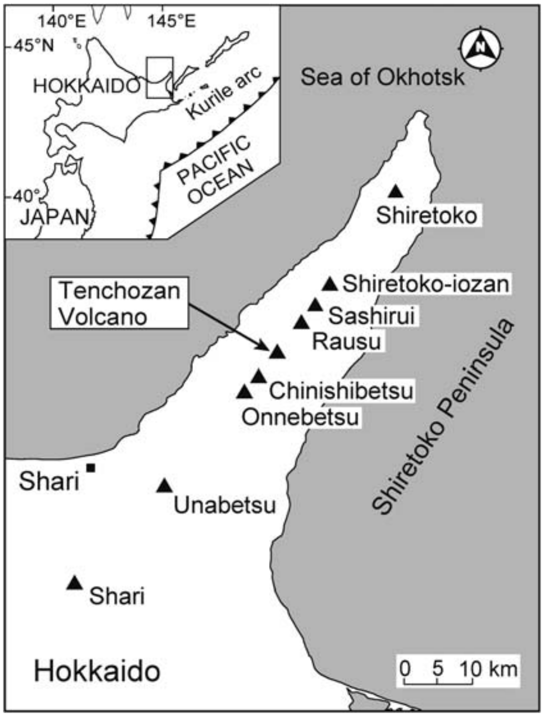

Fig. 1. Location of Tenchozan Volcano on the Shiretoko Peninsula, Hokkaido, Japan.

consisting of lithic fragments, pumice and ash (Fig. 4). The lithic fragments make up 25–30 vol.% of the tephra and are up to 8 cm across. They consist of subangular to subrounded andesites of various compositions. The andesites are gray to reddish brown, and vary in state of oxidation (non-oxidized to intensely oxidized) and alteration (fresh to intensely altered). The fresh andesite lithic fragments are identical in petrographical features (phenocryst assemblage and size) to the Tenchozan Lavas.

The pumice accounts for 10–15 vol.% of the Ten-a tephra and shows an upward increase in proportion within the tephra layer. The pumice is pale gray, subrounded, up to 9 cm across (Fig. 5), and commonly thickly coated with a pale brown, fine-grained ash. The pumice consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, and opaque minerals. Table 1 lists the whole-rock major-element chemical composition of the pumice (sample numbers Ten-1 A and -1B), which contains 62–63 wt.% SiO2.

The ash (~60 vol.% of the tephra) consists of altered rock fragments, plagioclase, augite, hypersthene, magnetite, and fresh volcanic glass. The altered rock fragments are petrographically identical to the larger lithic fragments. The volcanic glass is vesicular and shows a pumice-like habit (cf., Yoshikawa, 1976; Machida and Arai, 2003). X-ray diffraction (XRD) analysis of the $<2\mu$m fraction (separated by hydraulic elutriation) revealed the presence of opal-CT and minor cristobalite. XRD analysis with ethylene glycol treatment suggests the absence of clay minerals.

Figure 6 shows the grain-size distribution of the Ten-a tephra sampled at the type locality. Because the matrix is partly cohesive, sieving was performed in a water bath. The Ten-a tephra has a high proportion of grains ranging from 1/4 to 2 mm in diameter (-1 to 2 ϕ). Median diameter (Mdϕ) of the sieved sample is 0.0, and standard deviation ($\sigma\phi$, Inman, 1952) is 3.4.

3–3 Stratigraphy and radiocarbon ages

Representative stratigraphic logs of the Ten-a tephra are shown in Figure 7. At location 1 (the type locality), the geological section consists of (from lower to upper): the Miocene Rausugawa Formation (Doi *et al*., 1970; thickness >5 m), a debris-flow deposit (1.8 m), a volcanic ash (1 cm), the Rausudake pyroclastic flow deposit (Miyaji *et al*., 2000; 11 m), a reworked pyroclastic deposit (2 m), the Ten-a tephra (50 cm), and the surface soil (30 cm). The lowermost Rausugawa Formation comprises greenish, intensely altered, tuffacious breccia, consisting of angular andesite clasts, up to 15 cm across, embedded in a fine-grained matrix. The formation yields a fission-track age of 7.8 ± 0.9 Ma (Koshimizu and Kim, 1986). The overlying debris-flow deposit is pale brown and composed of subangular andesite cobbles, 5–10 cm across, in a sandy matrix.

The volcanic ash is pale gray, fine grained, non-laminated, and consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, and opaque minerals. The volcanic ash is inferred to be a fallout tephra derived from Rausu Volcano, because the ash is positioned just beneath the Rausudake pyroclastic flow deposit and is identical in mineral assemblage to the deposit.

The Rausudake pyroclastic flow deposit is gray and composed of several flow units (Goto, 2009). Each unit is 0.5–1 m thick and consists of angular andesitic lithic clasts (1–10 cm across) and subrounded andesitic pumice clasts (<30 cm across) in a matrix of andesitic rock fragments (<5 mm across). The andesitic lithic clasts and pumice clasts contain phenocrysts of plagioclase, hypersthene, augite, and opaque minerals. The pyroclastic flow deposit has a ground surge layer (2–3 cm thick) at the base, which includes charcoal fragments and partially carbonized wood. Radiocarbon dating of a partially carbonized wood sample (number SP-2, Fig. 7), determined by Beta Analytic (Miami, USA), yields an age of 2310 ± 60 years BP (Table 2). Calibrated calendar ages, obtained using the IntCal04 calibration (Reimer *et al*., 2004; Talma and Vogel, 1993), are 2460–2290 and 2270–2160 cal BP (2σ, 95% probability). The Rausudake pyroclastic flow deposit

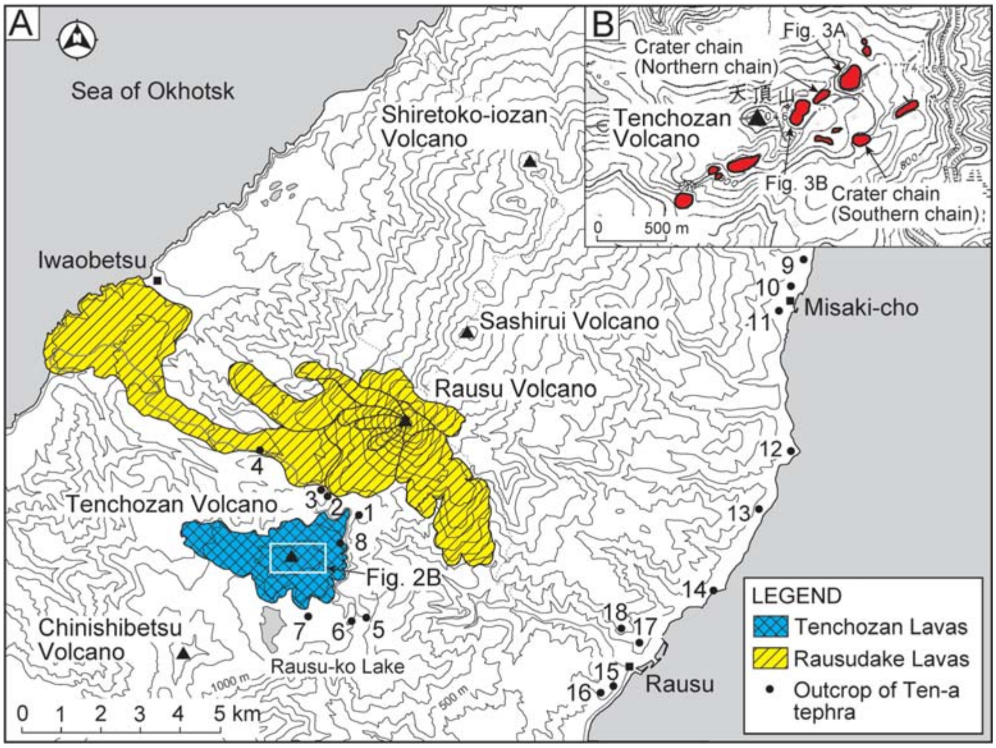

Fig. 2. (A) Distribution of the Tenchozan Lavas and the Rausudake Lavas. Outcrops of the Ten-a tephra are indicated by solid circles. Location numbers of the outcrops correspond to those in Fig. 7. Contour interval is 100 m. (B) Crater chains on the summit of the Tenchozan Volcano. The northern chain trends southwest–northeast, extends for 1800 m, and consists of 10 explosion craters. The southern chain trends southwest–northeast to west–east, extends for 700 m, and consists of four explosion craters. Contour interval is 20 m. Locations of Figs. 3A and 3B are also shown.

is capped by a reworked pyroclastic deposit (reworked Rausudake pyroclastic flow deposit), 2 m thick. The Ten-a tephra directly overlays the reworked pyroclastic flow deposit. The textures and components of the Ten-a tephra are described in Section 3-2. The tephra is overlain by a dark brown surface soil, 30 cm thick.

At locations 2 and 3, the geological sections show similar sequences to those observed in the upper part of section 1 (Fig. 7). At locations 4 and 5, the Ten-a tephra covers a debris-flow deposit. At location 4, the tephra contains a higher concentration of pumice (~20 vol.% of the tephra) than that observed at location 1. At location 5, the Ten-a tephra consists mainly of lithic fragments.

At location 6 (Ichino-ike Pond, 2 km east of Rausu-ko Lake), the geological section consists of (from lower to upper): a buried soil (>10 cm thick), a volcanic ash (2 cm), a second buried soil (3 cm), the Ten-a tephra (5 cm), and the surface soil (10 cm). The lowermost buried soil is dark brown and consists of peat. The overlying volcanic ash is pale gray, fine-grained, non-laminated, and consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, and opaque minerals. The volcanic ash corresponds to the volcanic ash below Rausudake pyroclastic flow deposit at location 1, because they are identical in mineral assemblage (plagioclase, hypersthene, augite, and opaque minerals) and stratigraphic location (below the Ten-a tephra). The ash is therefore inferred to have derived from Rausu Volcano (Goto, 2009). Radiocarbon dating of a soil sample, collected from the topmost one centimeter of the soil layer, located immediately below the volcanic ash, yields a conventional radiocarbon age of 2260±60 years BP and a calibrated calendar age of 2360–2130 cal BP (2σ, 95% probability, sample number TEN-54; Table 2). The second buried soil is dark brown and also consists of peat. The Ten-a tephra is pale brown and composed mainly of fresh to altered andesitic fragments up to 1 cm across. Radiocarbon dating of a soil sample, collected from the topmost one centimeter of the second soil layer, yields a conventional radiocarbon age of 1930±40 years BP and a calibrated calendar age

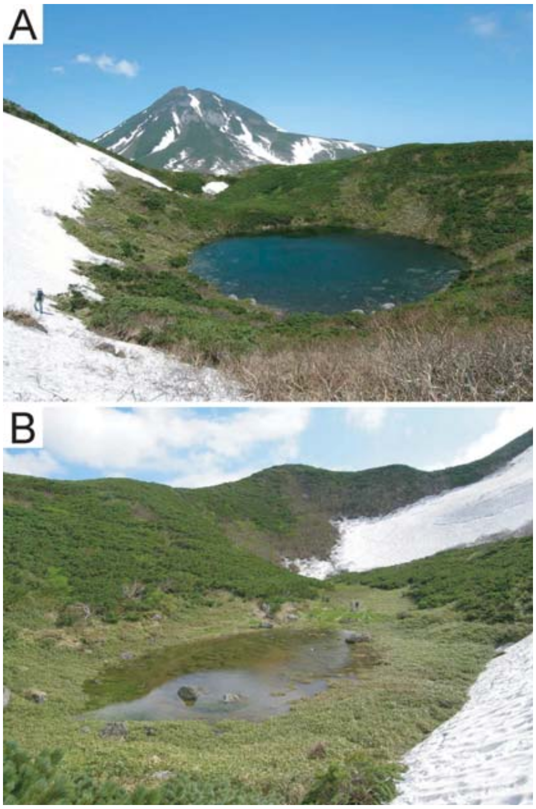

Fig. 3. Crater chains on the summit of Tenchozan Volcano. (A) An explosion crater of the northern chain viewed from the southwest. The diameter of the crater is 250 m. This crater is filled with cold water, forming a 56-m-wide lake. Note the person (left) for scale. The mountain behind the crater is Rausu Volcano. (B) An explosion crater of the northern chain viewed from the northeast. This crater is filled with water in springtime, forming a shallow 20-m-wide lake, but is dry from summer until autumn.

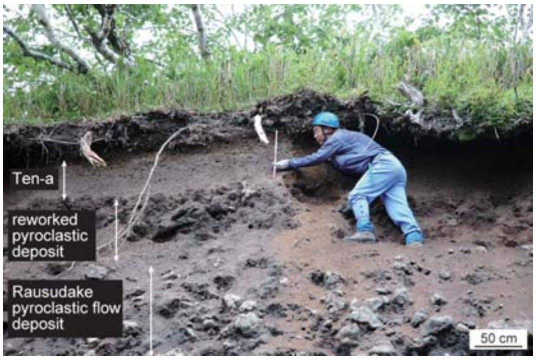

Fig. 4. Ten-a tephra (Ten-a) at the type locality (100 m east of Shiretoko Pass; Loc. 1 in Fig. 2). The tephra is 50 cm thick, pale brown, and composed of lithic fragments, pumice and ash. It overlies the Rausudake pyroclastic flow deposit, which is capped by a reworked pyroclastic deposit. Note the person for scale. Scale bar is 50 cm long.

Fig. 5. Pumice in the Ten-a tephra. The photograph was taken after washing the sample in the laboratory. Before washing, the pumice had been coated by a fine-grained ash.

of 1960–1810 cal BP (2σ, 95% probability, sample number TEN-51; Table 2). The Ten-a tephra is overlain by the dark brown surface soil, 10 cm thick.

3–4 Distribution and volume

The thickness distribution and maximum grain size of the Ten-a tephra are shown in Figures 8A and 8B, respectively. The maximum grain size was calculated as the average long-axis diameter of the three largest lithic clasts. These data suggest that the tephra increases in thickness and maximum grain size toward the summit of the Tenchozan Volcano. The bulk volume of the tephra, calculated following Hayakawa (1985) and using the 5-cm isopach, is $4.2\times10^7\,m^3$.

4. Discussion

4–1 Origin of the Ten-a tephra

The Ten-a tephra increases in thickness and maximum grain size toward the summit of Tenchozan Volcano, suggesting the tephra was erupted from the volcano. The tephra is inferred to have formed by phreatomagmatic explosions because the tephra is composed of non-juvenile lithic fragments that are interpreted to have formed by fragmentation of the pre-existing volcano surface, and fresh subrounded pumice, interpreted to be juvenile pyroclasts formed by the fragmentation and ejection of magma. The volume ($4.2\times10^7\,m^3$) and grain-size distributions of the Ten-a tephra (high pro-

Table 1. Whole-rock major-element compositions of andesites from the Tenchozan Lavas (samples Ten-13, -14, -15, -16, -18, -20) and pumice from the Ten-a tephra (Ten-1A and -1B), as determined by X-ray fluorescence (Rigaku RIX-2000) at Shimane University, Japan, following the analytical method proposed by Kimura and Yamada (1996).

	Tenchozan Lavas						Ten-a tephra (pumice)	
Sample No.	TEN-13	TEN-14	TEN-15	TEN-16	TEN-18	TEN-20	TEN-1A	TEN-1B
SiO_2 (wt. %)	58.41	57.93	58.45	57.42	60.81	61.21	62.20	62.91
TiO_2	0.80	0.81	0.80	0.83	0.77	0.75	0.76	0.74
Al_2O_3	16.61	16.52	16.53	16.73	16.41	17.46	16.08	16.10
Fe_2O_3*	8.48	8.60	8.50	8.87	7.69	6.85	6.99	6.87
MnO	0.19	0.18	0.19	0.18	0.17	0.15	0.17	0.16
MgO	3.81	3.90	3.64	3.87	2.94	2.71	2.48	2.35
CaO	6.97	7.15	6.99	7.21	6.03	5.48	5.59	5.42
Na_2O	3.21	3.15	3.21	3.06	3.11	3.28	3.42	3.44
K_2O	1.17	1.20	1.16	1.20	1.63	1.65	1.68	1.73
P_2O_5	0.18	0.17	0.18	0.18	0.15	0.17	0.11	0.12
Total	99.83	99.61	99.65	99.55	99.71	99.71	99.48	99.84
L.O.I.	0.21	-0.07	-0.03	0.30	1.44	3.12	1.84	2.26

Fe_2O_3* = total iron as Fe_2O_3. L.O.I. = loss on ignition. Sample locations (latitude, longitude): Ten-13 (44°02′48″N, 145°05′42″E), Ten-14 (44°02′48″N, 145°05′42″E), Ten-15 (44°02′49″N, 145°05′36″E), Ten-16 (44°02′48″N, 145°05′33″E), Ten-18 (44°02′41″N, 145°06′16″E), Ten-20 (44°02′44″N, 145°05′23″E), Ten-1A and -1B (44°03′17″N, 145°06′24″E).

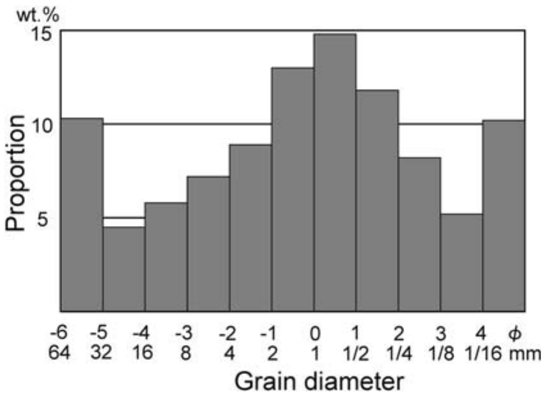

Fig. 6. Grain-size histogram of the Ten-a tephra, sampled from 100 m east of the Shiretoko Pass (the type locality; Loc. 1 in Fig. 2). The sample was sieved at intervals of 1 ϕ (where $\phi = -\log_2 d$, with d being the grain size in millimeters), using a set of sieves ranging from −6 to 4 ϕ (64 mm to 1/16 mm). The sieving was carried out in a water bath because the samples were partly cohesive. The sieved samples were dried and weighed to 0.01 g on a laboratory balance.

portion of grains smaller than 2 mm; Fig. 6) are consistent with phreatomagmatic explosions (see Morrissey *et al*., 2000). The pumice in the tephra is thickly coated with a pale brown, fine-grained ash, implying steam-rich eruptions. The crater chains at the summit of the Tenchozan Volcano are composed of a number of small explosion craters (diameter: 100–250 m in the northern chain, 70–100 m in the southern chain) and are consistent with steam-driven, multiple-vent-forming, explosive eruptions (cf., the 1910 eruption at Usu Volcano: Yokoyama *et al*., 1973; the 2000 eruption at Usu Volcano: Ui *et al*., 2002). The crater chains are thus inferred to have formed during the same eruptions as those that produced the Ten-a tephra. Volcanic Explosivity Index (VEI, Newhall and Self, 1982) of the eruptions is 3.

4–2 Eruption age

Previous geochronological studies (Orlova and Panychev, 1993; Okuno *et al*., 1997; Xu *et al*., 2004) suggested that the radiocarbon age of a buried soil located immediately below a mass-flow or pyroclastic deposit represents the emplacement age of the deposit. The radiocarbon ages of the buried soil immediately below the Ten-a tephra (sample TEN-51) and a volcanic ash (sample TEN-54) may represent the emplacement ages of the tephra and ash. The TEN-51 age for the Ten-a tephra (1930±40 years BP) and the TEN-54 age for the volcanic ash (2260±60 years BP) are consistent with the stratigraphic positions of these deposits (Fig. 7). The TEN-51 age for the Ten-a tephra (1930±40

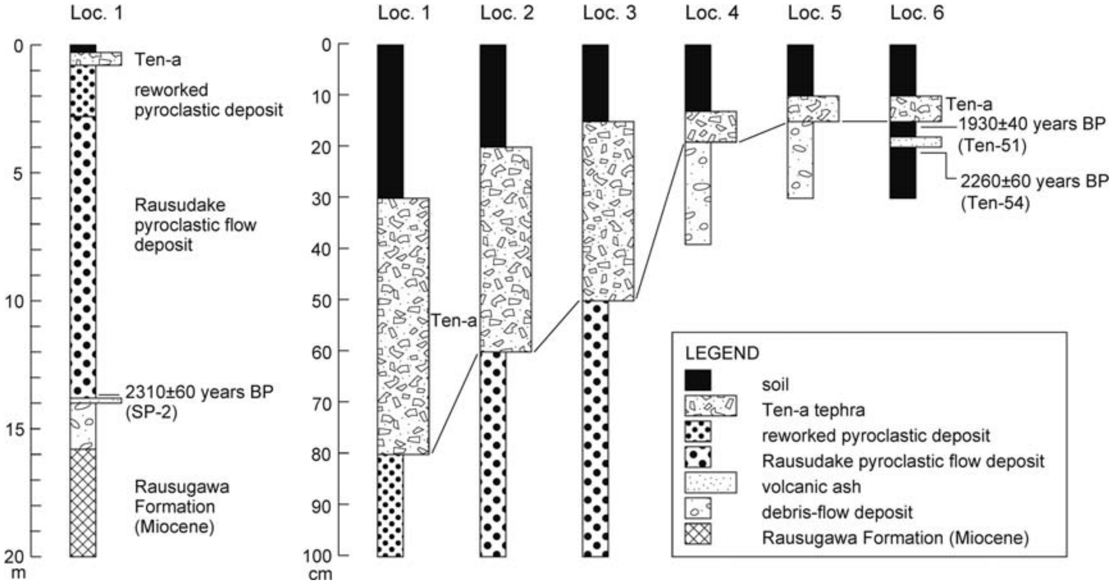

Fig. 7. Stratigraphic sections of the Ten-a tephra. Location numbers of the sections correspond to those in Figure 2. The section at location 1 is shown at small and large scales. Radiocarbon ages are also shown.

Table 2. Results of radiocarbon dating.

Sample number	Sample location	Material	Method	^{14}C age* (years BP, ±1σ)	$\delta^{13}C$ (‰)	Conventional ^{14}C age** (years BP, ±1σ)	Lab code	Calibrated calendar age*** (years cal BP)
TEN-51	Ichino-ike	organic sediment	radiometric	1940±40	-25.7	1930±40	Beta-194638	1960-1810 (2σ) 1920-1830 (1σ)
TEN-54	Ichino-ike	organic sediment	radiometric	2270±60	-25.8	2260±60	Beta-194637	2360-2130 (2σ) 2340-2300, 2260-2160 (1σ)
SP-2	Shiretoko Pass	carbonized wood	radiometric	2290±60	-24.0	2310±60	Beta-184279	2460-2290, 2270-2160 (2σ) 2350-2320 (1σ)

^{14}C age* is based on Libby's half-life (5568 years), uncorrected by $\delta^{13}C$ values. Ages are expressed in BP (years before AD 1950) with an error range of 1σ. **The conventional ^{14}C age includes $\delta^{13}C$ correction. Ages are expressed in BP with an error range of 1σ. ***Calibrated calendar ages were calculated from the conventional ^{14}C ages, using the program developed by Talma and Vogel (1993), based on the IntCal04 calibration database (Reimer *et al*., 2004). Ages are expressed in cal BP with an error range of 2σ (95% probability) and 1σ (68% probability). Sample TEN-51 is a dark brown soil (grain size <0.5 mm), collected from the uppermost 1 cm of the 3-cm-thick buried soil layer located immediately below the Ten-a tephra at Ichino-ike Lake (Loc. 6 in Figs. 2 and 7, latitude 44°01′48″N, longitude 145°06′18″E). Acid wash pretreatment was done before radiocarbon dating. Sample TEN-54 is a dark brown soil (grain size <0.5 mm), collected from the uppermost 1 cm of the 10-cm-thick buried soil layer located immediately below a volcanic ash at Ichino-ike Lake (Loc. 6). Acid wash pretreatment. Sample SP-2 is a partly carbonized wood (size 4×4×6 cm), collected from a ground surge layer at the base of the Rausudake pyroclastic flow deposit, located 100 m east of Shiretoko Pass (Loc. 1, 44°03′17″N, 145°06′24″E). Acid-alkali-acid wash pretreatment.

years BP) is also consistent with the stratigraphy at location 1, where the tephra overlies the Rausudake pyroclastic flow deposit, which yields a radiocarbon age of 2310±60 years BP (Fig. 7, sample SP-2). The TEN-51 sample (1930±40 years BP) yields a calibrated calendar age of 1960–1810 cal BP, suggesting the Ten-a tephra was emplaced at *ca*. 1.9 ka. This age is consistent with the well-preserved morphology of the crater chains on the summit of the volcano. Therefore, it is inferred that Tenchozan Volcano erupted at *ca*. 1.9 ka, resulting in the formation of the crater chains.

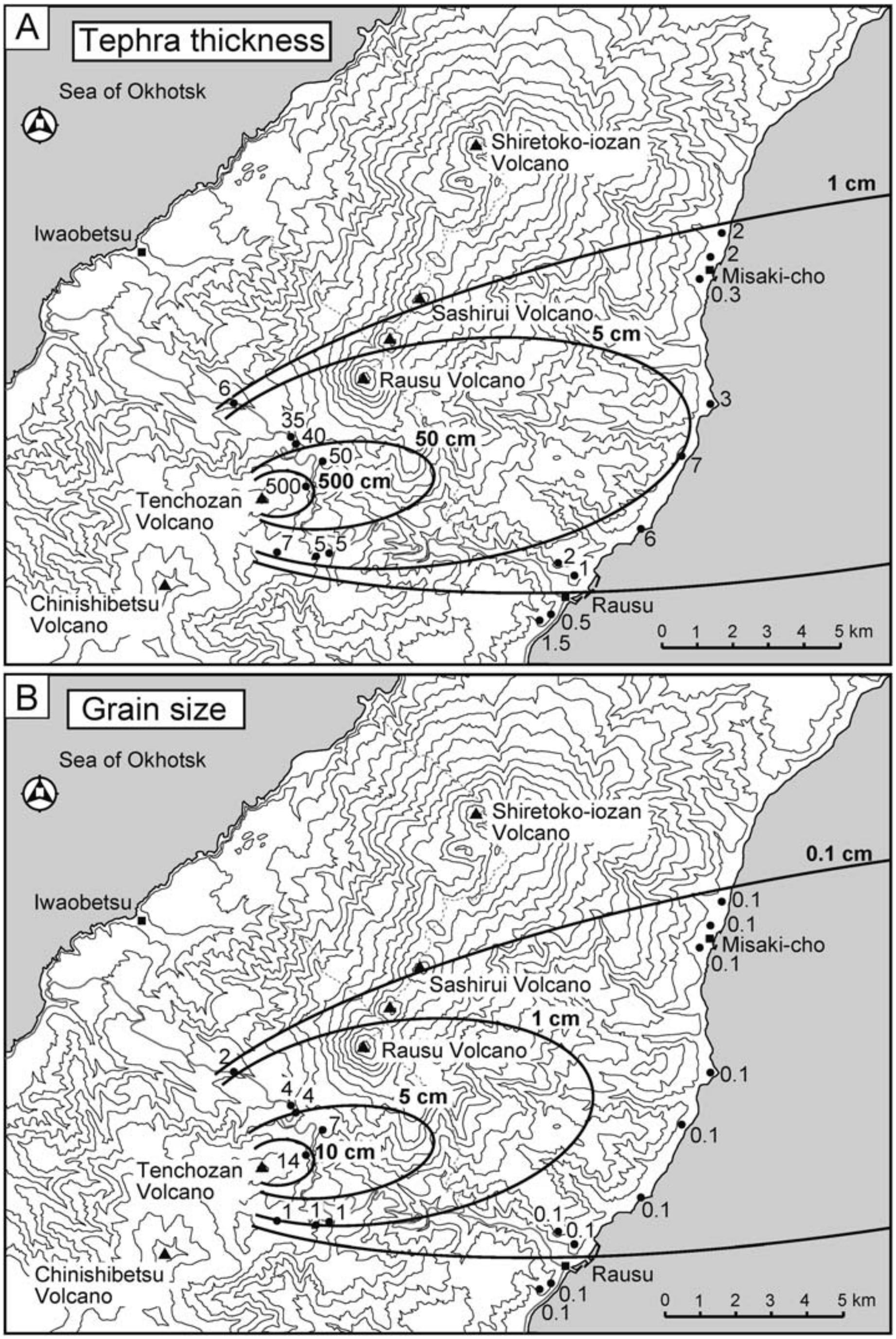

Fig. 8. (A) Thickness distribution of the Ten-a tephra (in cm). (B) Grain-size distribution of the Ten-a tephra (in cm). The maximum grain size is determined by the average of the long-axis diameters of the three largest lithics. The tephra increases in thickness and maximum grain-size toward the summit of Tenchozan Volcano.

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北海道知床半島，天頂山火山の降下テフラ

後藤芳彦

北海道東部知床半島の天頂山は，安山岩質溶岩からなる小型の火山で，山頂部には北東－南西方向に配列する爆裂火口列がある．本論では，天頂山の爆裂火口列を形成した降下テフラ（Ten-a）の分布と年代を明らかにした． Ten-a テフラは天頂山の山頂部から知床半島の東海岸に分布し， 東北東方向に伸長する分布主軸を示す．テフラは，新鮮～変質した安山岩質の石質岩片と新鮮な軽石からなり，マグマ水蒸気噴火の噴出物であると考えられる．テフラ直下の土壌層から得られた放射性炭素年代値は，1930±40 years BP（1960−1810 cal BP）である．天頂山は約 1900 年前に噴火し，山頂部に爆裂火口列を形成したと考えられる．