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Radiocarbon Dating of the Minamidake Debris-Avalanche Deposit, Shiretoko-iozan Volcano, Eastern Hokkaido, Japan

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Mt. Shiretoko-iozan is a Quaternary andesitic composite volcano located on the Shiretoko Peninsula, eastern Hokkaido, Japan. An amphitheatre at the summit and a debris-avalanche deposit (Minamidake Debris-Avalanche Deposit) at the western foot of the volcano suggest that sector collapse occurred during its eruptive history. Three trenches (6.8, 7.3, and 4.2 m deep) were dug at the western terminus of the Minamidake Debris-Avalanche Deposit in order to date the sector collapse event. The stratigraphic section consists of (from lower to upper): the Sashiruidake Lower Lava, a debris-flow deposit, a buried soil, a debris-flow deposit, a buried soil, the Minamidake Debris-Avalanche Deposit, a buried soil, the Ta-c tephra, and the surface soil. Radiocarbon dating of a buried soil located immediately beneath the Minamidake Debris-Avalanche Deposit yields an age of 3740±40 years BP (4230–4190 and 4190–3980 years cal BP), suggesting that the sector collapse occurred at *ca.* 4 ka.

Key words: debris-avalanche deposit, radiocarbon age, sector collapse, Shiretoko-iozan Volcano, trench survey

1. Introduction

Mt. Shiretoko-iozan is a Quaternary andesitic composite volcano located on the Shiretoko Peninsula, eastern Hokkaido, Japan (Fig. 1). An amphitheatre at the summit (the Minamidake Crater; Katsui *et al*., 1982) and a debris-avalanche deposit at the western foot of the volcano (the Minamidake Debris-Avalanche Deposit; Katsui *et al*., 1982) suggest that sector collapse occurred during its eruptive history, although the timing of this event remains unknown. We conducted a trench survey and performed radiocarbon dating of a buried soil located immediately beneath the debris-avalanche deposit to clarify the timing of the sector collapse event.

2. Shiretoko-iozan Volcano

Shiretoko-iozan Volcano (elevation of 1563 m above sea level, base diameter 10 km) is the largest Quaternary stratovolcano on the Shiretoko Peninsula (Fig. 2). The volcanic edifice consists mainly of andesitic lavas (Katsui *et al*., 1982) that yield K–Ar ages of 0.24±0.03, 0.16±0.02, and 0.05±0.04 Ma, suggesting stratovolcano-building activity began at *ca.* 0.24 Ma and continued for more than 200,000 years (Goto *et al*., 2000).

An amphitheatre (2 km across) occurs just south of the summit and opens to the west (Fig. 2). The Minamidake Debris-Avalanche Deposit (Katsui *et al*., 1982) extends from the amphitheatre to the western foot of the volcano, and details of the deposit are described in section 3. Katsui *et al*. (1982) suggested that a violent explosion triggered collapse of the northwestern part of the volcano summit and that the subsequent debris avalanche cascaded down the northwest flank.

The base of the amphitheatre is partly filled with the Namakoyama Lava Dome and the Nanpo Lava. The Namakoyama Lava Dome, located in the middle part of the amphitheatre, is 1000 m across, 220 m thick, and grades to the west into a lava flow that extends for 4000 m (Namakoyama Lava, Fig. 2). The Nanpo Lava, located on the northern rim of the amphitheatre, comprises three lava lobes extending to the northeast, west, and south, respectively, over distances of 700–1500 m. No geochronological data have been reported for the Namakoyama Lava Dome or the Nanpo Lava.

The volcano is active, with recorded eruptions occurring in 1857, 1876, 1889, and 1935 (Katsui *et al*., 1982). These historic eruptions took place at a parasitic crater on the northwestern flank of the volcano (Fig. 2) and were characterized by phreatic explosions with extrusions of large amounts of sulphur (Watanabe, 1940).

3. Minamidake Debris-Avalanche Deposit

The Minamidake Debris-Avalanche Deposit is 6 km long (trending E–W), 3 km wide (N–S), up to 30 m

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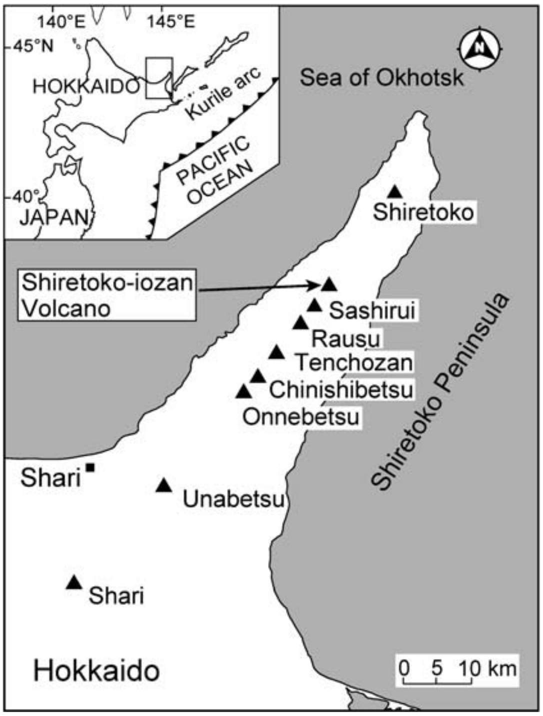

Fig. 1. Location map of Shiretoko-iozan Volcano on the Shiretoko Peninsula, eastern Hokkaido, Japan.

thick, and covers an area of 11.7 km^2 (Fig. 2). The deposit retains its primary morphological features, including hummocky topography and a distal cliff (terminology following Ui *et al*., 2000). The hummocky topography is prominent in the western part of the deposit. The hummocks are 10–100 m across with 5–20 m of relief. Several lakes are nested within the hummocky terrain (Shiretoko-goko Lakes; Fig. 3). The distal cliff is located at the terminus of a westerly lobe of the debris-avalanche deposit (Fig. 3). The well-preserved cliff is 10–20 m high and has a slope of 30°–40°. The interior of the deposit is exposed at a site located 4 km west of the amphitheatre (Katsui *et al*., 1982), where the deposit is 15–20 m in exposed thickness, massive (non-stratified), matrix supported, very poorly sorted, and composed of fresh to altered andesite clasts up to 2 m across in a matrix of lithic fragments. The clasts consist of olivine–hypersthene–augite andesite and hypersthene–augite andesite.

4. Trench surveys

Stratigraphic and geochronological studies of the Minamidake Debris-Avalanche Deposit are hampered by limited exposures due to thick vegetation cover. We conducted a trench survey of the deposit to determine the stratigraphic record of events and to collect a buried soil sample from immediately beneath the debris-ava-

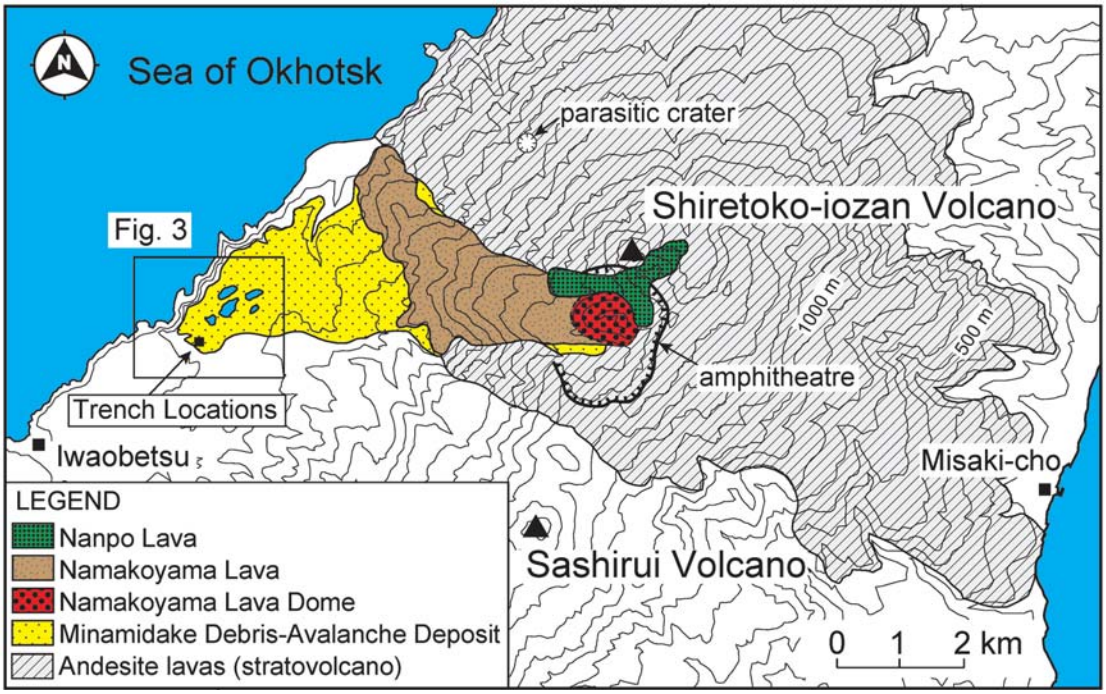

Fig. 2. Simplified geological map of Shiretoko-iozan Volcano (modified from Katsui *et al*., 1982). Contour interval is 100 m.

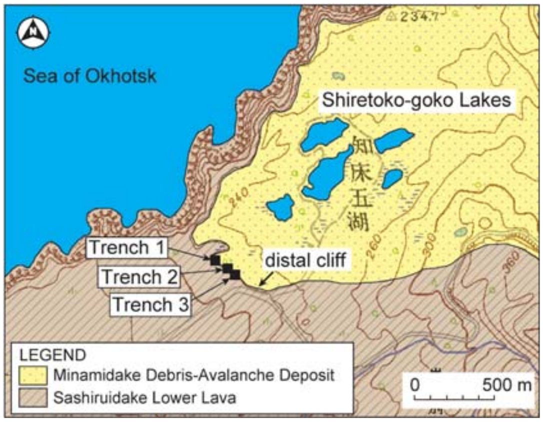

Fig. 3. Locations of trench sites at a distal cliff on the western edge of the Minamidake Debris-Avalanche Deposit. The deposit occurs above the Quaternary Sashiruidake Lower Lava.

lanche deposit, for radiocarbon dating. To minimize the digging depth, a distal cliff on the western terminus of the deposit was selected for the trench sites (Fig. 3). Three trench sites on the slope of the cliff were selected on the basis of aerial photographs and field surveys (trenches 1–3; Fig. 3). At these sites, the Minamidake Debris-Avalanche Deposit (10–20 m thick) occurs above the Quaternary Sashiruidake Lower Lava (>200 m thick; Katsui *et al*., 1982) derived from Sashirui Volcano.

The trenches were excavated on 18 October 2006, using a 2.9-tonne backhoe (Komatsu PC-200) with a 0.7 m^3 bucket. Trench 1 was 5 m wide, 10 m long, and 6.8 m deep (Fig. 4); trench 2 was a 5×5 m square, 7.3 m deep; and trench 3, adjoining trench 2, was a 5×5 m square, 4.2 m deep. The observation faces of trenches 1 and 2 were oriented N–S, perpendicular to the flow direction of the deposit, whereas that of trench 3 was oriented E–W, parallel to the flow direction.

5. Geological sections

5–1 Trench 1

The stratigraphic section in trench 1 consists of a subhorizontal sequence comprising (from lower to upper) the Sashiruidake Lower Lava, a debris-flow deposit, a buried soil, a debris-flow deposit, a second buried soil, the Minamidake Debris-Avalanche Deposit, a third buried soil, a volcanic ash, and the surface soil (Fig. 5A).

The Sashiruidake Lower Lava (thickness>30 cm) consists of a massive interior and a blocky surface composed of angular lava blocks (50–100 cm across) with curviplanar surfaces. The lava consists of grey porphyritic andesite containing phenocrysts of plagioclase, augite and hypersthene.

Fig. 4. Photograph of the Minamidake Debris-Avalanche Deposit in trench 1. The deposit occurs above a debris-flow deposit capped by a 10-cm-thick soil layer. Sample GK-22 (collected for radiocarbon dating) was taken from the uppermost 1 cm of this soil layer. Scale bar is 1 m.

The debris-flow deposit (thickness>19 cm) above the lava is brown, matrix supported, very poorly sorted, and composed of andesite boulders up to 50 cm across embedded in a fine-grained, clay-rich matrix. The debris-flow deposit grades upwards into a dark brown soil layer (1 cm thick).

The overlying debris-flow deposit (thickness, 430 cm) is yellowish brown, matrix supported, very poorly sorted, and composed of andesite boulders up to 100 cm across embedded in a fine-grained, clay-rich matrix. The boulders show reverse grading, with large boulders concentrated in the uppermost part of the deposit. The matrix contains a high concentration of volcanic glass. The debris-flow deposit grades upwards into a dark brown soil layer, 10 cm thick (Fig. 4).

The Minamidake Debris-Avalanche Deposit (thickness, 160 cm) sharply overlies the 10-cm-thick soil layer (Fig. 4). The deposit is pale brown, massive (nonstratified), matrix supported, very poorly sorted, nongraded, and composed of angular to subangular andesite clasts up to 40 cm across in an inhomogeneous, fine- to coarse-grained matrix. The andesite clasts are com-

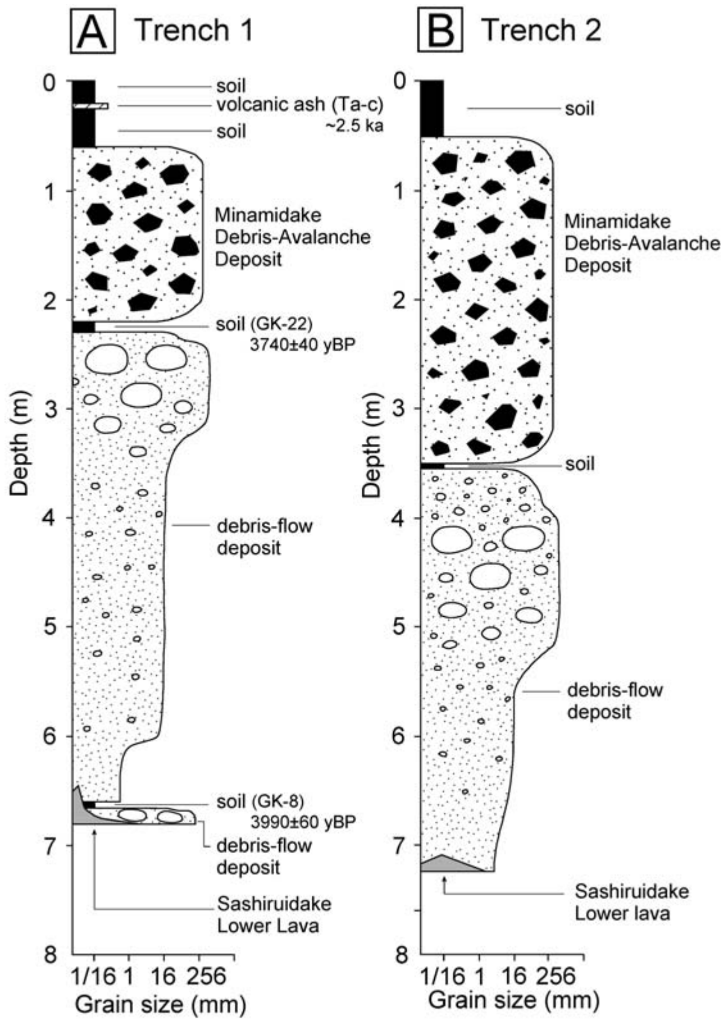

Fig. 5. Stratigraphic cross-sections of trench 1 (A) and trench 2 (B), showing the locations of samples collected for radiocarbon dating (GK-22 and GK-8).

posed of fresh to altered olivine–hypersthene–augite andesite and hypersthene–augite andesite. No jigsaw cracks (Ui *et al*., 2000) were observed in the clasts. The matrix consists mainly of andesitic rock fragments up to 5 mm across, and locally contains amoeboid patches (5–10 cm) of pale grey, clay-rich ash. The debris-avalanche deposit is overlain by a dark brown soil layer, 27 cm thick (Fig. 5A).

The volcanic ash (thickness, 3 cm) located immediately below the surface soil layer is reddish brown, fine-grained, well sorted, and non-laminated. It consists of fresh volcanic glass and crystals of plagioclase, hypersthene, augite, opaque minerals, and minor olivine. The volcanic glass is mainly pumice-shaped (see Machida and Arai, 2003) and has a hydrated rim, 1–2 μm thick (see Nakamura *et al*., 2002). The refractive index of the volcanic glass (hydrated rim) ranges from 1.4991 to 1.5124 (mean, 1.506; mode, 1.508; Kyoto Fission-Track Co. Ltd.). The refractive index of hypersthene ranges from 1.700 to 1.719 (mean, 1.711; mode, 1.711). The mineral assemblage, refractive index, presence of hydrated rim, and geographic location of the ash suggest it is the Tarumai-c tephra (Ta-c) (Ishikawa *et al*., 1972; Machida and Arai, 2003; Nakamura *et al*., 2002) derived from Tarumai Volcano, southwest Hokkaido. The volcanic ash is overlain by dark brown surface soil, 20 cm thick.

5–2 Trench 2

The stratigraphic section in trench 2 consists of a subhorizontal sequence comprising (from lower to upper) the Sashiruidake Lower Lava, a debris-flow deposit, a buried soil, the Minamidake Debris-Avalanche Deposit, and the surface soil (Fig. 5B). The sequence resembles that in trench 1.

The Sashiruidake Lower Lava (thickness > 10 cm) is grey and massive, with a smooth surface. The petrographical features of the lava are identical to that in trench 1. The overlying debris-flow deposit (thickness, 370 cm) is yellowish brown and composed of andesite boulders (< 100 cm across) in a clay-rich matrix. The boulders show reverse grading, with large boulders concentrated in the middle to upper parts of the deposit. The deposit contains high concentrations of volcanic glass in the matrix and corresponds to the 430-cm-thick debris-flow deposit in trench 1. It grades upwards into a dark brown soil layer, 5 cm thick.

The Minamidake Debris-Avalanche Deposit (thickness, 300 cm) sharply overlies the 5-cm-thick soil layer and consists of angular to subangular andesite clasts (up to 130 cm across) in a fine- to coarse-grained matrix. The texture and lithology of the deposit are identical to those in trench 1. The deposit is covered by dark brown surface soil, 50 cm thick. This section does not contain the volcanic ash present in trench 1.

5–3 Trench 3

The stratigraphic section in trench 3 comprises a tapered sequence thinning to the west (Fig. 6), consisting of a debris-flow deposit, a buried soil, the Minamidake Debris-Avalanche Deposit, a clay-rich ash, and the surface soil (Fig. 6B).

The basal debris-flow deposit (thickness > 50 cm) is yellowish brown and composed of andesite boulders up to 20 cm across in a fine-grained, glass-rich matrix. This deposit corresponds to the uppermost part of the 370-cm-thick debris-flow deposit in trench 2. It grades upwards into a dark brown buried soil, 5 cm thick.

The Minamidake Debris-Avalanche Deposit, which sharply overlies the 5-cm-thick soil layer, is wedge-shaped and decreases in thickness westward from 350 to 0 cm (Fig. 6B). The deposit consists of angular to subangular andesite clasts (up to 130 cm across) in a fine- to coarse-grained matrix. The andesite clasts show a westward decrease in diameter from 130 to 30 cm. No jigsaw-fit texture was observed in the andesite clasts. A pale grey, clay-rich ash layer extends for 2.5 m westward from the terminus of the deposit (Fig. 6B). The layer is wedge-shaped (its thickness decreases westward from 50 to 0 cm), massive (non-stratified), non-graded, composed of intensely altered lithic fragments up to 1 mm across, and resembles the clay-rich ash in the matrix of the Minamidake Debris-Avalanche Deposit in trench 1. X-ray diffraction analysis indicates the clay-rich ash contains smectite, kaolinite, quartz, natroalunite, cristobalite, and talc. The Minamidake Debris-Avalanche Deposit is overlain by dark brown surface soil, 50–100 cm thick.

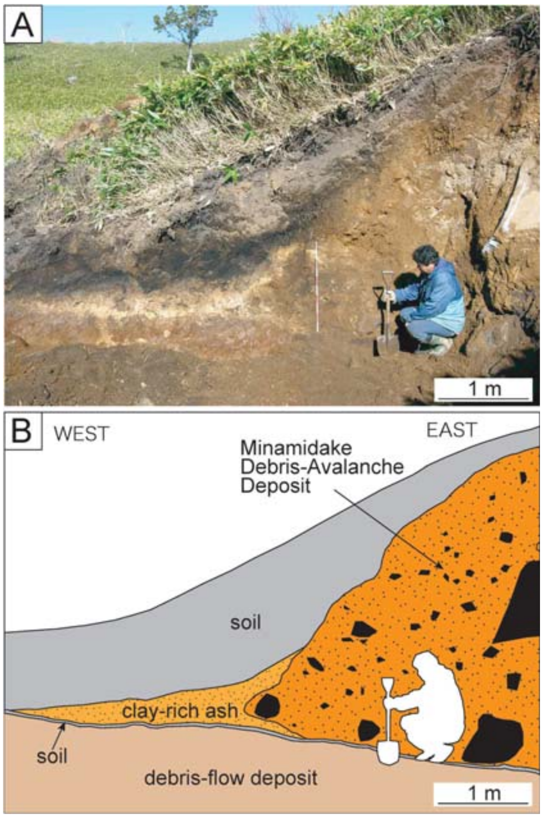

Fig. 6. Photograph (A) and accompanying sketch (B) of a longitudinal cross-section through the distal cliff of the Minamidake Debris-Avalanche Deposit exposed in trench 3. Scale bar is 1 m. The debris-avalanche deposit is wedge-shaped and decreases in thickness westward from 350 to 0 cm.

6. Radiocarbon dating

Radiocarbon ages were determined for two soil samples, both collected from trench 1 (samples GK-8 and GK-22; Fig. 5A). Sample GK-8 is a dark brown buried soil (organic sediment, grain size < 0.5 mm) collected from the entire thickness of the 1-cm-thick soil layer located immediately below the 430-cm-thick debris-flow deposit. The soil layer contains no modern plant-roots, and shows no sign of disturbance (*e.g.*, bioturbation, erosion) during or after deposition. Sample GK-22 is a dark brown buried soil (organic sediment, grain size < 1 mm) collected from the uppermost 1 cm of the 10-cm-thick buried soil layer located immediately below the Minamidake Debris-Avalanche Deposit. The soil layer contains no modern plant-roots, and shows no sign of disturbance during or after deposition.

Radiocarbon dating for both samples was performed by Beta Analytic (Miami, USA). Sample GK-8 was

Table 1. Radiocarbon ages of buried soils in trench 1.

Sample number	Material	Method	^{14}C age* (years BP, ±1σ)	δ^{13}C (‰)	Conventional ^{14}C age** (years BP, ±1σ)	Lab code	Calibrated calendar age*** (years cal BP)
GK-22	organic sediment	AMS	3740±40	-25.0	3740±40	Beta-227009	4230-4190, 4190-3980 (2σ) 4150-4080, 4040-4000 (1σ)
GK-8	organic sediment	radiometric	4000±60	-26.2	3990±60	Beta-224208	4780-4770, 4580-4290 (2σ) 4520-4410 (1σ)

The stratigraphic positions of the samples are shown in Fig. 5A. *Based on Libby's half-life (5568 years), uncorrected by δ^{13}C values. Ages are expressed in BP (years before AD 1950) with an error range of 1σ. **The conventional ^{14}C age includes δ^{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). AMS = accelerator mass spectrometry.

acid washed, and the remaining carbon was analysed using a standard radiometric method with extended counting, yielding a conventional radiocarbon age of 3990±60 years BP (error range 1σ, Table 1). Sample GK-22 was acid washed, and the remaining carbon was analysed using accelerator mass spectrometry (AMS), yielding a conventional radiocarbon age of 3740±40 years BP (error range 1σ, Table 1).

Calibrated calendar ages were calculated using the program developed by Talma and Vogel (1993) and based on the IntCal04 calibration database (Reimer *et al*., 2004). Calibrated calendar ages, calculated from the GK-8 conventional radiocarbon age (3990±60 years BP), are 4780–4770 and 4580–4290 years cal BP (2σ, 95% probability), and 4520–4410 years cal BP (1σ, 68% probability) (Table 1). The intercept of the conventional radiocarbon age with the calibration curve is 4430 years cal BP (2480 years cal BC). Calibrated calendar ages, calculated from the GK-22 conventional radiocarbon age (3740±40 years BP), are 4230–4190 and 4190–3980 years cal BP (2σ, 95% probability), and 4150–4080 and 4040–4000 years cal BP (1σ, 68% probability) (Table 1). The intercept of the conventional radiocarbon age with the calibration curve is 4090 years cal BP (2140 years cal BC).

7. Discussion

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, in the case that the deposit overlies the soil with no disturbance. In the case of the 430-cm-thick debris-flow deposit in trench 1, the soil shows no sign of disturbance, suggesting the debris flow conformably overlies the pre-existing ground surface without any disturbance. Therefore, the radiocarbon age of the buried soil immediately below the 430-cm-thick debris-flow deposit in trench 1 (sample GK-8; 3990±60 years BP; 4780–4770 and 4580–4290 years cal BP) is inferred to represent the emplacement age of the deposit. Thus, the 430-cm-thick debris-flow deposit is considered to have been emplaced at *ca.* 4.5 ka.

The radiocarbon age of a buried soil located immediately below a debris-avalanche deposit may also represent the emplacement age of the deposit, in the case that the debris avalanche conformably overlies the soil with no disturbance. In the case of the buried soil located immediately below the Minamidake Debris-Avalanche Deposit, the soil shows no sign of disturbance or erosion, suggesting the debris avalanche conformably overlies the pre-existing ground surface without any disturbance or removal of material. This preservation of the underlying soil is probably due to the location of the trench (at the terminus of the debris-avalanche deposit). We therefore infer that the radiocarbon age of the buried soil located immediately below the Minamidake Debris-Avalanche Deposit (sample GK-22; 3740±40 years BP; 4230–4190 and 4190–3980 years cal BP) represents the emplacement age of the deposit. Thus, the Minamidake Debris-Avalanche Deposit is inferred to have been emplaced at *ca.* 4 ka.

The age of sample GK-8, which dates the 430-cm-thick debris-flow deposit (*ca.* 4.5 ka), and the age of sample GK-22, which dates the Minamidake Debris-avalanche Deposit (*ca.* 4 ka), are consistent with the stratigraphic positions of these deposits (Fig. 5A). The ages are also consistent with the age and stratigraphic position of the Ta-c tephra, which was probably emplaced at *ca.* 2.5 ka (Furukawa and Nanayama, 2006) (Fig. 5A). We therefore conclude that the sector collapse of the Shiretoko-iozan Volcano occurred at *ca.* 4 ka.

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(Editional handling Noriko Hasebe)

北海道東部知床硫黄山，南岳岩屑なだれ堆積物の放射性炭素年代

後藤芳彦・合地信生・松田　功

北海道東部知床硫黄山の南岳岩屑なだれ堆積物のトレンチ調査を行い，放射性炭素年代測定を行った．トレンチは知床五湖の南西 500 m の 3 地点で掘削し，掘削深度は 6.8 m，7.3 m，4.2 m である．トレンチの地質断面は，下位より，サシルイ岳下部溶岩，土石流堆積物，土壌層，土石流堆積物，土壌層，南岳岩屑なだれ堆積物，土壌層，Ta-c テフラ，表層土壌からなる．南岳岩屑なだれ堆積物直下の土壌層から得られた AMS 放射性炭素年代値は，3740±40 years BP（暦年較正年代値は 4230–4190, 4190–3980 years cal BP）である．知床硫黄山の山体崩壊は約 4 ka に起きたと考えられる．