

## VEGETATION CHANGES AROUND HAVEN LAKE, ADAK ISLAND, CENTRAL ALEUTIANS, ALASKA, DETERMINED FROM POLLEN ANALYSIS

Makoto Noguchi<sup>1</sup> • Toshiyuki Fujiki<sup>2\*</sup> • Mitsuru Okuno<sup>3</sup> • Lyn Gualtieri<sup>4</sup> • Virginia Hatfield<sup>5</sup> • Brenn Sarata<sup>6</sup> • Masayuki Torii<sup>7</sup> • Keiji Wada<sup>8</sup> • Toshio Nakamura<sup>9</sup> • Dixie West<sup>10</sup>

<sup>1</sup>Department of Applied Science, Graduate School of Science, Okayama University of Science, 1-1 Ridai-cho, Kita-ku, Okayama 700-0005, Japan.

<sup>2</sup>Department of Applied Science, Faculty of Science, Okayama University of Science, 1-1 Ridai-cho, Kita-ku, Okayama 700-0005, Japan.

<sup>3</sup>Department of Earth System Science, Faculty of Science, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan.

<sup>4</sup>Civil and Environmental Engineering, Seattle University, 901 12th Avenue Seattle, WA 98122, USA.

<sup>5</sup>Museum of the Aleutians, 314 Salmon Way, PO BOX 648, Unalaska, AK 99685 USA.

<sup>6</sup>Fugro Engineers BV, Prismastraat 4, 2631 RT, 2630 AC, Nootdorp, The Netherlands.

<sup>7</sup>Disaster Mitigation Laboratory, Center for Water Cycle, Marine Environment and Disaster Management, Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto 860-8555, Japan.

<sup>8</sup>Hokkaido University of Education, 9 Kitamon-cho, Asahikawa, Hokkaido 070-8621, Japan.

<sup>9</sup>Institute for Space-Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan.

<sup>10</sup>Biodiversity Institute and Natural History Museum, The University of Kansas, 1345 Jayhawk Blvd. Lawrence, KS 66045, USA.

**ABSTRACT.** We collected peat sediments (sediment core ADK13083002) from Haven Lake on the north side of Adak Island (central Aleutian Islands, Alaska) to determine whether the vegetation has changed. We confirmed the presence of six tephra layers, including Forty Years (0.3 cal ka BP), T2, YBO (3.3 cal ka BP), Intermediate (6.4 cal ka BP), Main (9.5 cal ka BP), and T6. We identified four major pollen assemblage zones (HL-1 to HL-4, in descending order) in the cored sediment. HL-1 was dominated by Ranunculaceae and *Empetrum* pollen; H-2 was dominated by Poaceae, Ranunculaceae, and *Empetrum* pollen; HL-3 was dominated by Poaceae and *Empetrum* pollen; and HL-4 was dominated by Poaceae, Cyperaceae, *Lycopodiaceae*, and *Empetrum* pollen. Small charcoal particles, likely transported from a distance, were found at low frequencies until 6.4 cal ka BP. The total cross-sectional area of charcoal particles increased to 1500  $\mu\text{m}^2$  or more by 6.4 cal ka BP, implying that the large charcoal particles originated from nearby Aleut settlements, which were established around the same time.

**KEYWORDS:** AMS radiocarbon dating, pollen analysis, vegetation change.

## INTRODUCTION

The volcanic Aleutian Islands form an arc from the Alaska Peninsula to the Kamchatka Peninsula of Russia, as shown in Figure 1. Adak Island of the Andreanof Islands group lies in the central Aleutians. Studies of vegetation changes in the Aleutian Islands have previously been conducted on Adak Island (Heusser 1978), Atka Island (Heusser 1990), and Attu Island (Heusser 1990). Heusser (1978) described a paleovegetation change on Adak Island by identifying three major pollen assemblages: (1) Cyperaceae-*Salix*-*Empetrum*-*Lycopodium* (before 10 cal ka BP), (2) Cyperaceae-Poaceae (10–3 cal ka BP), and (3) *Empetrum* (after 3 cal ka BP). The climate of the early and late Holocene was cold and windy, whereas the middle Holocene was characterized by a warm climate; the author of that study also concluded that the change in vegetation resulted from climatic variation, not volcanic ash fall. Many dated tephra layers are interspersed within the Adak sediments; therefore, it is possible to conduct a detailed chronological analysis (Black 1976).

\*Corresponding author. Email: fujiki@das.ous.ac.jp.

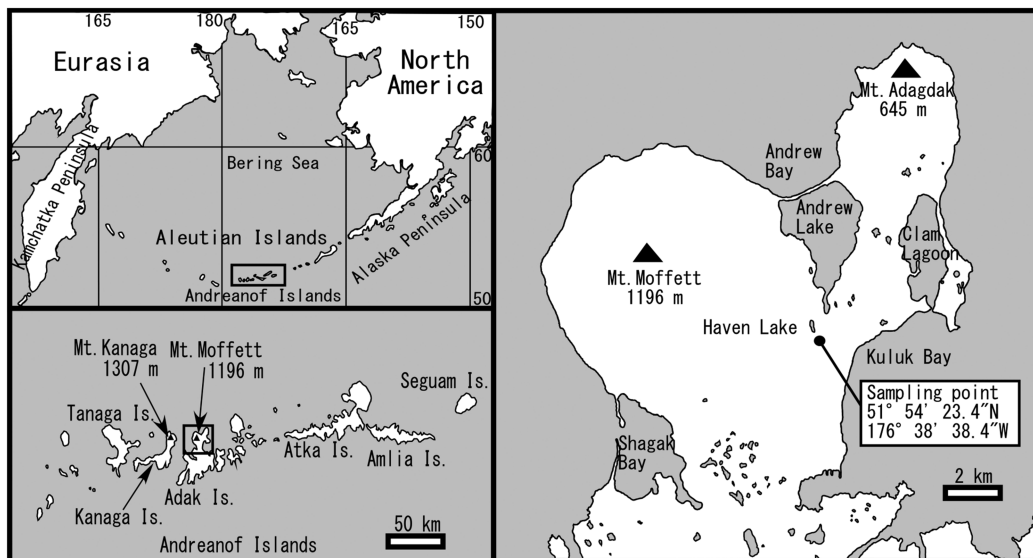


Figure 1 Map showing location of sampling point.

To examine vegetation changes on Adak Island, a 233-cm-long sediment core (ADK13083002) was collected from Haven Lake in the northern part of the island in August 2013. Accelerator mass spectrometry (AMS) radiocarbon dating of a peat sample was conducted, and the pollen sequences and charcoal particle contents of the sediments were examined. Here, we present these data and discuss the paleovegetation and human activities on Adak Island.

## STUDY SETTING AND STRATIGRAPHY

### Climate and Vegetation

Adak Island has an oceanic climate, with summer temperatures averaging 7–11°C and winter temperatures near freezing. The average annual precipitation is 1525 mm, with high humidity. Fog, low clouds, and storms frequently occur during the winter months due to the influence of the Aleutian Low (van der Leeden and Troise 1974). Trees are practically nonexistent on Adak Island, while dwarf shrubs such as *Salix arctica* and *S. reticulata* occur (Hultén 1960). The current grassland vegetation is characterized by herb and heath (Bank 1952; Hultén 1960). The herb vegetation consists primarily of Poaceae, such as *Poa arctica*, *Agrostis borealis*, and *Trisetum spicatum*; Cyperaceae, such as *Carex dioica*, *C. saxatilis*, and *Juncus arcticus*; Ranunculaceae, such as *Coptis trifolia*, *Anemone narcissiflora*, and *Ranunculus reptans*; and Apiaceae, such as *Ligusticum scoticum*, *Angelica lucida*, and *Conioselinum chinensis*. The heath vegetation consists largely of the dwarf shrubs *Empetrum nigrum* and *Phyllodoce aleutica* subsp. *aleutica*; and furthermore *Loiseleuria procumbens*, *Cassiope lycopodioides*, *Vaccinium uliginosum* subsp. *microphyllum*, and *V. vitis-idaea* subsp. *minus* also occur (Heusser 1978).

### Stratigraphy

We used a peat sampler to collect a 233-cm-long peaty sediment core (ADK13083002) near Haven Lake (51°54'23.4"N, 176°38'38.4"W; Figure 1), and detected the following six tephra layers: T1 tephra from 14–18 cm, T2 tephra from 40–44 cm, T3 tephra from 72–79 cm, T4 tephra from 121–128 cm, T5 tephra from 154–176 cm, and T6 tephra from 196–200 cm (Figure 2).

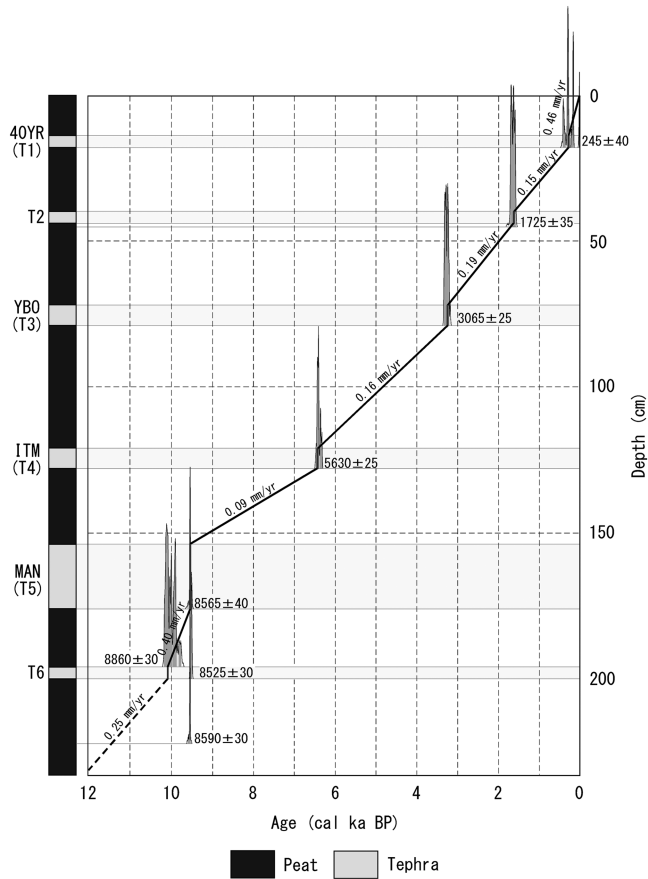


Figure 2 Columnar section showing the stratigraphy and age-depth profile of ADK13083002 core.

## ANALYTICAL METHODS

### AMS $^{14}\text{C}$ Dating

Seven vascular plant samples were dated using the AMS  $^{14}\text{C}$  method. Samples were chemically cleaned with acid-alkali-acid (AAA) treatment and combusted to  $\text{CO}_2$ . The resulting  $\text{CO}_2$  was cryogenically purified and catalytically converted to graphite (Kitagawa et al. 1993). The  $^{14}\text{C}$  age of each sample was measured along with standards using the HVEE Tandem AMS system at Nagoya University (Nakamura et al. 2004), the NEC 15SDH-2 AMS system (JAEA-AMSTONO) at Tono Geoscience Center, JAEA (Saito-Kokubu et al. 2015), or the NEC Peletron 9SDH-2 AMS system at the Institute of Accelerator Analysis, Ltd. (IAA). The systems measured all three carbon isotopes in both samples and the NIST oxalic acid (HOxII) standard.

The  $^{14}\text{C}$  content of dead graphite was also measured to estimate the  $^{14}\text{C}$  background level. The  $^{14}\text{C}$  contents of the samples and the standard were calculated by subtracting the  $^{14}\text{C}$  concentration from the background  $^{14}\text{C}$  concentration. We corrected for carbon isotopic fractionation using the  $^{13}\text{C}/^{12}\text{C}$  ratio ( $\delta^{13}\text{C}_{\text{PDB}}$ ) measured by AMS. The  $^{14}\text{C}$  error was evaluated by the  $^{14}\text{C}$  reproducibility of repeated sample and standard measurements and errors in  $^{14}\text{C}$  background removal calculations. Conventional  $^{14}\text{C}$  dates were calibrated to a calendar year

timescale using the IntCal13 dataset (Reimer et al. 2013) and the CALIB 7.1 computer program (Stuiver and Reimer 1993).

### Pollen and Charcoal Analyses

We collected several grams of sediment for pollen analysis at 10-cm increments along the length of the core. Fossil pollen and spores were extracted by treatment with 10% KOH, a ZnCl<sub>2</sub> solution, and Erdtman's acetolysis method (Erdtman 1934). Following acetolysis, samples were dehydrated using an ethanol series (30, 60, and 99.5%) and treated with xylene for pollen analysis. The samples were then mounted in Eukitt medium (Fujiki et al. 2014) for observation under a light microscope. Over 500 pollen grains (excluding spores) were counted in each sample. The percentage of each taxon was based on the total pollen count. Identification of fossil pollen was based on Nakamura (1980a, 1980b) and Fujiki et al. (2016), and that of fossil spores was based on Nasu and Seto (1986a, 1986b). The species-level identification of trilete type fern spores, such as *Lycopodium* and *Selaginella*, was based on Heusser and Pettet (1988). Charcoal particles in the sample were also counted and their cross-sectional areas were measured using a Nikon DS Camera Control Unit DS-L3.

## RESULTS

### Radiocarbon Dating and Sedimentation Rate

The AMS <sup>14</sup>C dating of eight samples yielded ages of 8590 ± 30 BP (IAAA-171947) for 223–222 cm, 8525 ± 30 BP (IAAA-171948) for 201–200 cm, 8860 ± 30 BP (IAAA-172211) for 196–195 cm, 8565 ± 40 BP (NUTA2-19292) for 177–176 cm, 5630 ± 25 BP (IAAA-171949) for 128–129 cm, 3065 ± 25 BP (IAAA-172212) for 79–78 cm, and 1725 ± 35 BP (JAT-14005) for 46–45 cm, and 245 ± 40 BP (NUTA2-25673) for 18–19 cm (Table 1; Figure 2). Their calendar ages were ca. 9.5, 9.5, 10.1, 9.5, 6.4, 3.3, 1.6 and 0.3 cal ka BP, respectively (Table 1).

Table 1 Results of AMS <sup>14</sup>C dating using plant fragments.

Depth (cm)	δ <sup>13</sup> C <sub>PDB</sub> (‰)	<sup>14</sup> C date (BP)	Age range (cal BP) (2σ probability %)	Laboratory code
18–19	–29	245 ± 40	0–21 (6.5%) 144–216 (29.2%) 266–332 (44.1%) 355–433 (20.2%)	NUTA2-25673
45–46	–27	1725 ± 35	1556–1710 (100.0%)	JAT-14005
78–79	–26	3065 ± 25	3210–3358 (100.0%)	IAAA-172212
128–129	–26	5630 ± 25	6319–6375 (25.1%) 6386–6475 (74.9%)	IAAA-171949
176–177	–28	8565 ± 40	9480–9563 (97.3%) 9571–9584 (1.8%) 9587–9595 (0.9%)	NUTA2-19292
195–196	–26	8860 ± 25	9792–9844 (5.1%) 9868–9874 (0.6%) 9886–9975 (27.8%) 9980–10157 (66.6%)	IAAA-172211
200–201	–26	8525 ± 30	9485–9541 (100.0%)	IAAA-171948
222–223	–26	8590 ± 30	9505–9506 (0.1%) 9516–9602 (99.9%)	IAAA-171947

We compared this stratigraphic description with the obtained  $^{14}\text{C}$  ages as well as the existing stratigraphic description (Black 1976; O'Leary 2001; Okuno et al. 2012; Krawiec et al. 2013) and correlated the four tephra as follows: T1 tephra from 14–18 cm is Forty Years (40YR), T3 tephra from 72–79 cm is YBO, T4 tephra from 121–128 cm is Intermediate (ITM), and T5 tephra from 154–176 cm is Main (MAN) (Figure 2). Okuno et al. (2012) and Krawiec et al. (2013) reported eruption ages of 0.4, 3.6, 7.2, and 9.5 cal ka BP for 40YR, YBO, ITM, and MAN, respectively.

Because the tephra was deposited rapidly, the sedimentation rate of the core was calculated using the same age between, above, and below the tephra (Figure 2). The sedimentation rate between the T6 and MAN tephra is ca. 0.40 mm/yr. The sedimentation rate decreased from the MAN to ITM tephra (ca. 0.09 mm/yr). The sedimentation rate increased from the ITM to 40YR tephra (ca. 0.15–0.19 mm/yr). The sedimentation rate further increased from 40YR to the upper layer (0.46 mm/yr). The average sedimentation rate above the T6 tephra (ca. 0.25 mm/yr) was applied as the sedimentation rate below the T6 tephra.

### Pollen Assemblages

We identified 35 varieties of fossil pollen grains and spores, which were classified as non-arboreal pollen (NAP) and spores (S). The NAP included *Pinus*, *Betula*, *Alnus*, *Salix*, *Ilex*, *Empetrum*, Poaceae, Cyperaceae, *Fritillaria*, Rosaceae, *Myriophyllum*, *Linnaea*, *Geranium*, Onagraceae, *Polygonum*, Caryophyllaceae, *Anemone*, *Coptis*, other Ranunculaceae, Apiaceae, *Artemisia*, and other Asteraceae, while the S included monolete type, *Lycopodium alpinum*, *L. annotinum*, *L. clavatum*, *L. complanatum*, *L. inundatum*, *L. selago*, *L. sitchense*, *Selaginella selaginoides*, *S. wallacei*, *S. watsonii*, and Sphagnaceae.

Figure 3 shows the pollen and spore data. *Empetrum* and Poaceae pollen grains and Lycopodiaceae spores were dominant in all layers. The core was divided into four zones (HL-1, HL-2, HL-3, and HL-4) based on pollen composition.

#### HL-4 (233–176 cm; 11.8–9.5 cal ka BP)

*Alnus* pollen and pollen of the dwarf shrub *Salix* were minimal, and *Salix* pollen disappeared above the T6 tephra layer. The *Alnus* pollen concentration was very low in all layers. *Empetrum* pollen increased near the T6 layer, but decreased above it. Conversely, Poaceae pollen decreased near the T6 layer, but increased above it. Cyperaceae pollen was dominant throughout HL-4. Asteraceae pollen, including *Artemisia*, decreased, while monolete type spores rapidly increased above the T6 layer. *Lycopodium annotinum* and *L. clavatum* spores were present in high concentrations, while *Selaginella selaginoides* spores were present in low percentages beneath the T6 layer. The number of *L. selago* spores decreased near the T6 layer. Sphagnaceae spores increased beneath the T6 layer.

#### HL-3 (154–124 cm; 9.5–6.4 cal ka BP)

*Betula* pollen appeared in this zone, and was present in low amounts in the remaining pollen zones. Cyperaceae pollen, monolete-type *Lycopodium annotinum*, and *L. clavatum* spores, decreased. Apiaceae pollen increased slightly, but then decreased throughout the HL-3 zone. Ranunculaceae pollen concentrations, including those of *Anemone* and *Coptis*, were low, but increased over time. The numbers of *Lycopodium* spores decreased rapidly, while those of Sphagnaceae spores decreased slightly. *Selaginella selaginoides* spores were not present.

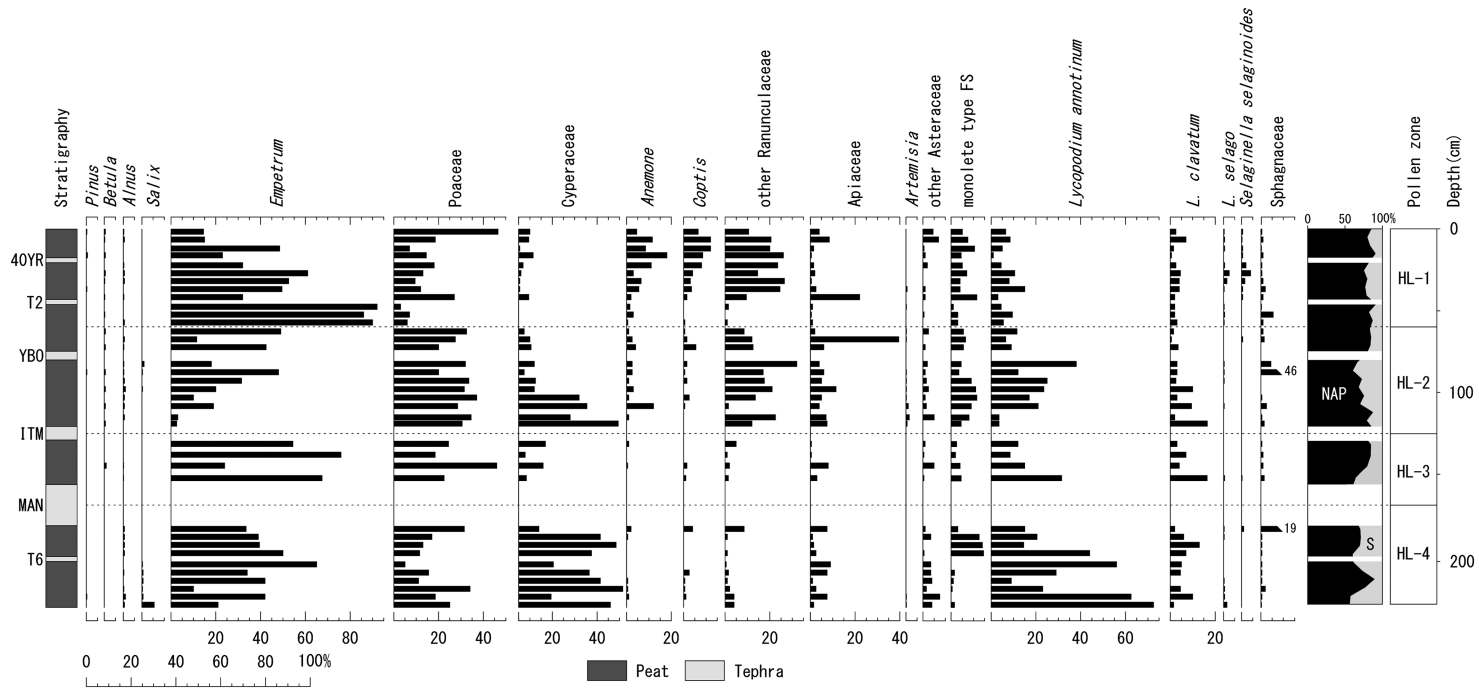


Figure 3 Pollen and spore diagram for ADK13083002 core.

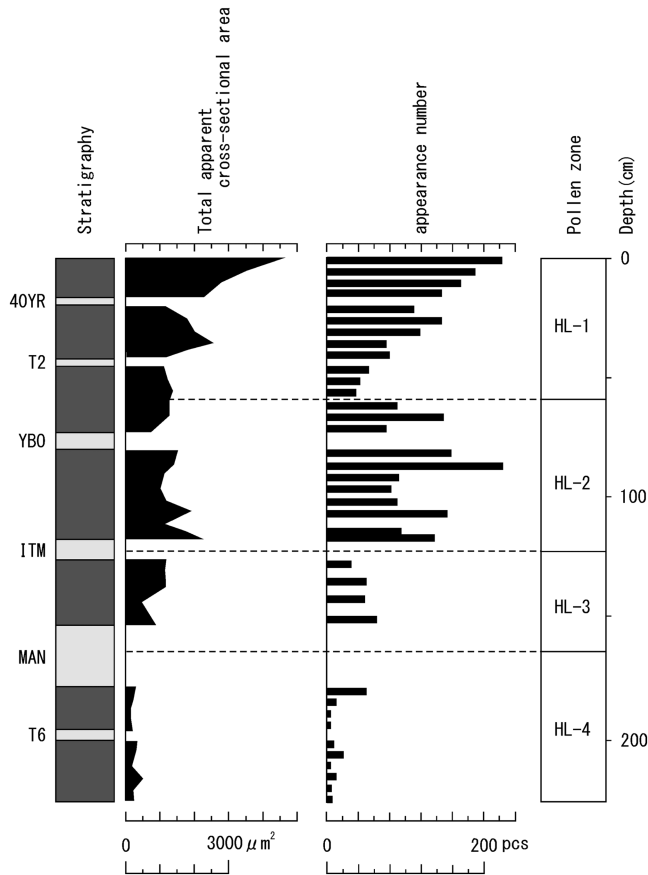


Figure 4 Charcoal particle diagram for ADK13083002 core.

#### *HL-2 (121–60 cm; 6.4–2.3 cal ka BP)*

*Pinus* and *Salix* pollen grains reappeared in low amounts, but *Salix* pollen disappeared above the YBO layer. *Empetrum* pollen drastically decreased just above the ITM tephra layer, but then began to increase. Cyperaceae pollen increased above the ITM tephra layer, but decreased above 100 cm. Ranunculaceae pollen, including those of *Anemone* and *Coptis*, increased above the ITM tephra layer, but decreased above the YBO layer. Apiaceae pollen increased rapidly at 70 cm and was found in higher concentrations than in the HL-3 zone. Monolete-type and *Lycopodium* spores increased above the ITM tephra layer, and then decreased above the YBO layer.

#### *HL-1 (60–0 cm; 2.3 cal ka BP–present)*

*Empetrum* pollen decreased, while other herb pollen grains and spores increased above the T2 tephra layer. *Lycopodium selago* and *Selaginella selaginoides* spores appeared above the T2 tephra layer.

#### **Charcoal Analysis**

Charcoal particles with a cross-sectional area of approximately  $10\ \mu\text{m}^2$  were present in all layers. There were 25–50 charcoal particles in the HL-4 zone and approximately 50 particles in

the HL-3 zone. The numbers of charcoal particles increased to more than 100 above the HL-2 zone (Figure 4). Furthermore, charcoal particles with an area of  $400\ \mu\text{m}^2$  or larger appeared above the HL-2 zone. The total cross-sectional areas of charcoal particles were  $100\text{--}500\ \mu\text{m}^2$  in the HL-4 zone,  $500\text{--}1000\ \mu\text{m}^2$  in the HL-3 zone, and  $1000\text{--}2000\ \mu\text{m}^2$  in the HL-2 zone; areas increased suddenly to  $1500\text{--}4500\ \mu\text{m}^2$  above the HL-1 zone (Figure 4).

## DISCUSSION

### Vegetation Changes

The presence and percentages of pollen grains changed above and below the tephra layers. *Lycopodium selago* and *Selaginella selaginoides* spores, indicative of a cold climate (Heusser and Peteet 1988; Takiya and Hagiwara 1997), appeared in the HL-4 and HL-1 zones. These results support findings from Heusser (1978) that imply the climate was relatively dry and windy until 9.5 cal ka BP and after 1.5 cal ka BP, but relatively warm from 9.5 to 1.5 cal ka BP. As in Heusser (1978), no *Salix* pollen was detected from ca 9.5 to 4.7 cal ka BP. This phenomenon is thought to be because of the disappearance of willows as dwarf shrubs that grow in lowland, such as *Salix barclayi*, due to transgression in the warm period (Heusser 1978), and the *Salix* currently distributed in Adak Island is thought to be a species that cannot grow at low altitude (Heusser 1978). *Empetrum* plants are short, have small, needle-like ericoid leaves, and can tolerate strong and cold winds, fog, and freezing temperatures. Therefore, this plant can grow in very windy environments where other species cannot survive (Koizumi 2009). In the period when the percentage of *Empetrum* pollen was high, we think that strong winds from the Aleutian Low dominated. It is thought that the increase in Poaceae pollen in the middle of the HL-1 zone was an effect of T2 tephra fall (Heusser 1978). The same phenomenon occurred at Tashiro Mire at Aomori, Japan (Kito et al. 2017), and Utasai Bog in Hokkaido, Japan (Hughes et al. 2013). Regarding the cause of this phenomenon, Kito et al. (2017) suggested that deposition of volcanic ash formed an impermeable layer that raised the water level. Hughes et al. (2013) speculated that tephra supplied nutrients and minerals to the water. *Pinus*, *Betula*, and *Alnus* plants do not currently grow on Adak Island. These fossil pollen grains were also detected by Heusser (1978), as well as in our analysis. These fossil pollen grains have also been detected on other islands where the plants do not now grow naturally, and we think that westerlies blew the pollen grains to Adak Island. The percentages of *Pinus*, *Betula*, and *Alnus* pollen grains were slightly higher on Attu Island (Heusser 1990) than on Atka and Adak Islands. Therefore, it is possible that the pollen grains were transported from the Kamchatka Peninsula and Commander Islands (Heusser 1990). The *Pinus* pollen is considered to be from *Pinus pumila* distributed in the Kamchatka Peninsula and Commander Islands, and the *Betula* and *Alnus* pollen grains are thought to be pollen grains of *Betula nana* subsp. *exilis* and *Alnus crispa* subsp. *Simulate* distributed in the Kamchatka Peninsula (Hultén 1960; Heusser 1990).

### Charcoal Particles and Aleut Settlement

Aleuts, the indigenous people of the Aleutian Islands, migrated from east to west across the Aleutian Islands (Laughlin et al. 1979). Aleuts settled in the eastern Aleutians approximately 9.0 cal ka BP (Davis and Knecht 2010), arrived in the central Aleutians by approximately 6.0 cal ka BP (O'Leary 2001; Savinetsky et al. 2012), and reached the far western Aleutians by approximately 3.2 cal ka BP (West et al. 1999). We hypothesize that the  $10\text{-}\mu\text{m}^2$  charcoal particles in the HL-4 and HL-3 zones were transported to Adak Island from a distance. The numbers of charcoal particles, and especially of those with a cross-sectional area of  $500\text{--}1000\ \mu\text{m}^2$ , increased suddenly above the ITM tephra layer (Figure 4). Aleut shell mounds were also discovered just above the ITM tephra layer (Okuno et al. 2007; Savinetsky et al. 2012);



therefore, it is possible that the large charcoal particles were transported to Adak Island from nearby Aleut settlements. These results support the earlier evidence that Aleuts settled on Adak Island after deposition of the ITM tephra at locations such as the Tutiakoff site (village ADK-171; Savinetsky et al. 2012). Therefore, we think that the vegetation also changed from 6.4 cal ka BP due to anthropogenic activity.

## CONCLUSIONS

We conducted pollen and charcoal analyses on a peat sediment core collected from Haven Lake on Adak Island in the central Aleutian Islands. Our results imply changes in paleovegetation that correspond with the settlement of Aleuts on the island. Heath and grassland were the dominant vegetation, and four zones, HL-1, HL-2, HL-3, and HL-4, were identified based on the composition of pollen. These results support the earlier evidence that Aleuts settled on Adak Island approximately 7.2 cal ka BP.

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