Application of pollen analysis to dating of ice cores from lower-latitude glaciers

Fumio Nakazawa,[1] Koji Fujita,[2] Jun Uetake,[3] Mika Kohno,[4] Toshiyuki Fujiki,[2] Serguei M. Arkhipov,[5] Takao Kameda,[6] Keisuke Suzuki,[7] and Yoshiyuki Fujii[4]

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[1] Ice cores from temperate regions have long been expected to be useful for understanding local climate trends, but a reliable dating method has proved difficult. Here we show that measurements of pollen using samples with only 10 mL of water can give an accurate measure of the annual ice accumulation. In addition, two major types of pollen allow us to estimate the summer ice accumulation as well as the annual accumulation. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* pollen, glaciers, ice cores, middle and low-latitude, chronology, Aitai

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1. Introduction

[2] Studies of deep ice cores from Greenland and Antarctica have proven crucial for reconstructing past environmental history [e.g., *Lorius et al.*, 1990; *Jouzel et al.*, 1993; *Grootes et al.*, 1993; *McManus et al.*, 1994]. On the other hand, ice cores from lower-latitude glaciers (between about 60°N and 60°S), although covering a shorter timescale, can provide important climate information that is influenced by the local surroundings. However, ice core studies on lower-latitude glaciers have generally been limited to elevations above 4000 m above sea level (asl); specifically, Dunde (5325 m) [*Thompson et al.*, 1989], Guliya (6200 m) [*Thompson et al.*, 1995a], Dasuopu (7200 m) [*Thompson et al.*, 2000], and Belukha (4062 m) [*Olivier et al.*, 2003] in central Asia; Upper Fremont (4000 m) [*Naftz et al.*, 1996] in North America; Quelcaya (5670 m) [*Thompson et al.*, 1985], Sajama (6542 m) [*Thompson et al.*, 1998], and Huascaran (6048 m) [*Thompson et al.*, 1995b] in the Andes; and Kilimanjaro (5893 m) [*Thompson et al.*, 2002] in Africa. Few studies are done on such lower-latitude glaciers, mainly because summer melting distorts the annual signal from the seasonal variations in chemical concentrations and oxygen isotope ratios ($\delta^{18}O$) that are used to date polar ice cores. Thus other methods are needed. One study of a Himalayan ice core analyzed snow algae for ice core dating [*Yoshimura et al.*, 2000]. The study found that the detection and identification of snow algae below 5 m (i.e., over 8 years old) of the core is difficult due to autolysis or bacterial decomposition. Therefore algae analysis is limited to relatively recent ice.

[3] Thus to develop a dating method applicable to ice cores from lower-elevation and lower-latitude glaciers, we turned our attention to the seasonality of pollen preserved in an ice core. Previous pollen studies have been mainly done on arctic ice caps and glaciers [e.g., *Fredskild and Wagner*, 1974; *Lichti-Federovich*, 1975; *McAndrews*, 1984; *Bourgeois et al.*, 1985; *Short and Holdsworth*, 1985; *Koerner et al.*, 1988; *Bourgeois*, 1990, 2000], where the pollen mostly originates from sources hundreds to thousands of kilometers away, and thus the pollen concentrations in ice typically range from 10 to 100 grains L^{-1}. Only a few studies have investigated seasonal pollen variations in firn pits and ice cores [*Ambach et al.*, 1966; *Short and Holdsworth*, 1985; *Bourgeois*, 1990, 2000]. However, the cores were not dated in these studies because the methods required about 1000 mL per sample to get enough pollen, which exceeded the typical ice core sample volume of about 500 mL. On the other hand, lower-latitude glaciers are typically within a few tens of kilometers of significant pollen sources, and thus they typically have peak concentrations of at least 1 pollen grain mL^{-1} in the ice. Other merits of using pollen for ice core dating include the following: (1) pollen grains are deposited on glacier surfaces for only a few months of the year and with a peak period that is independent of the total pollen count but dependent on the species [*Iwanami*, 1980, pp. 168–170]; (2) the size of a pollen grain is between about 10 and 150 μm, which seems to help it to remain at its

[1]Graduate School of Science, Nagoya University, Nagoya, Japan.
[2]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan.
[3]Faculty of Bioscience and Biotechnology, Tokyo Institute of Technology, Tokyo, Japan.
[4]National Institute of Polar Research, Tokyo, Japan.
[5]Institute of Geography, Russian Academy of Sciences, Moscow, Russian Federation.
[6]Kitami Institute of Technology, Hokkaido, Japan.
[7]Department of Environmental Sciences, Faculty of Science, Shinshu University, Nagano, Japan.

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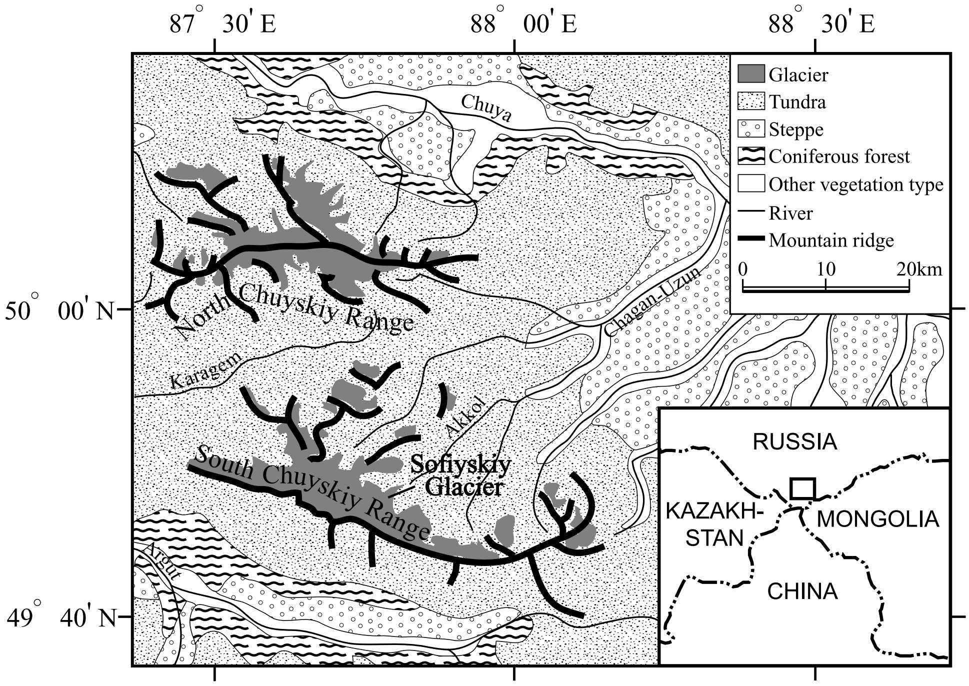

Figure 1. Vegetation map surrounding the southern Chuyskiy Range, based on a vegetation map by *Janvareva* [1978].

original depth despite meltwater incursion; and (3) the sporopollenin, which is the outer shell of the pollen, protects the pollen from decay, and thus pollen can be preserved even in 130,000-year-old ice [*McAndrews*, 1984]. Furthermore, as no pollen sources peak in winter, the concentration of pollen in the winter layer is typically less than 0.5 grains mL^{-1} [*Haeberli et al.*, 1983]. In addition, the pollen type may allow one to estimate the layers in different seasons.

2. Study Area and Methods

[4] Sofiyskiy glacier (49°47′N, 87°43′E) is one of the major glaciers in the central part of the South Chuyskiy

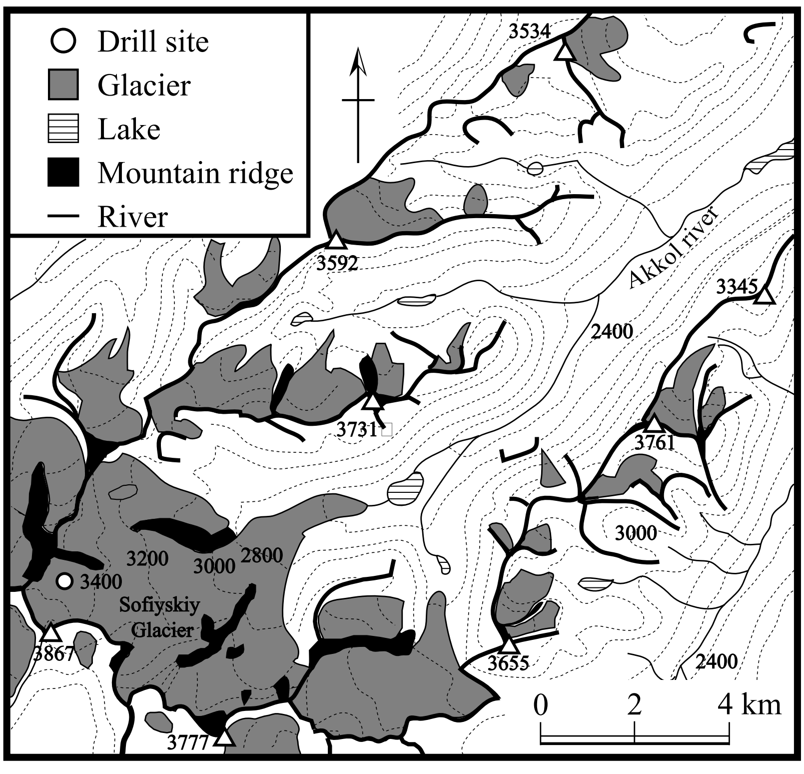

Figure 2. Topographic map and location of Sofiyskiy glacier.

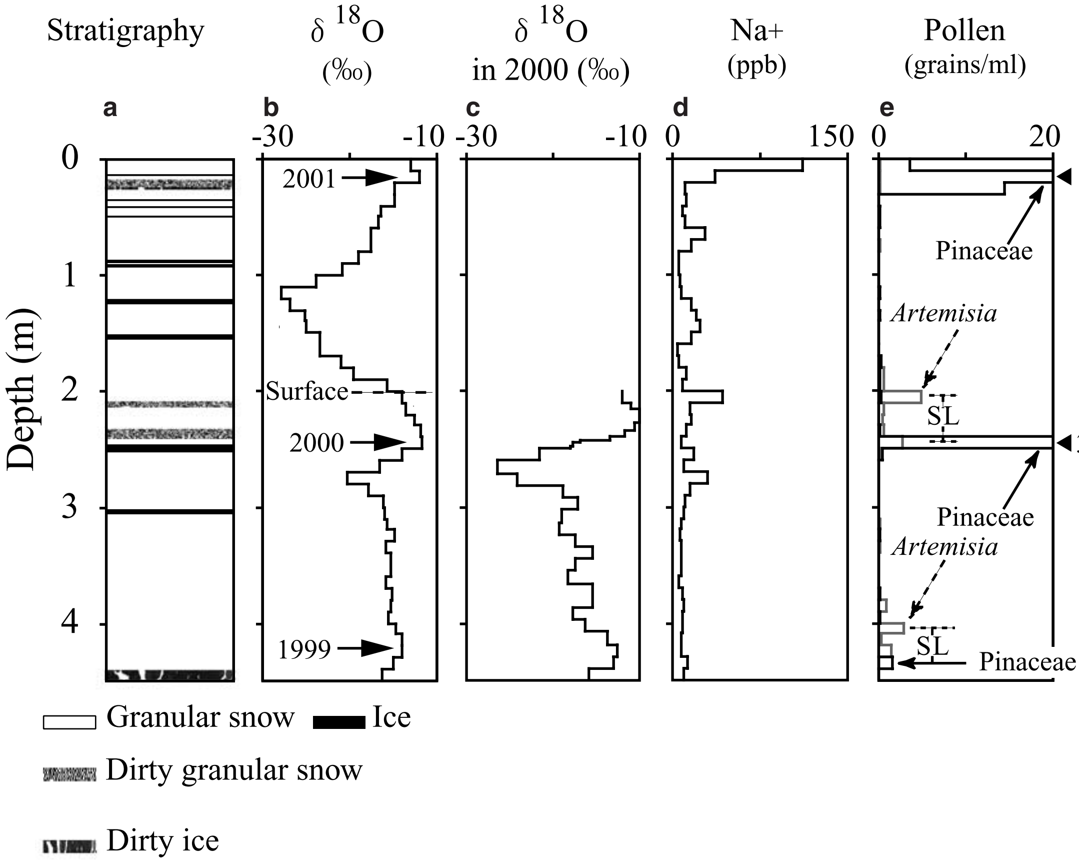

Figure 3. Vertical profiles from the pit samples on Sofiyskiy glacier. (a) Physical stratigraphy measured in July 2001. (b) Oxygen isotope ratios ($\delta^{18}O$) measured in July 2001. (c) Profiles of $\delta^{18}O$ measured at the same site in July 2000 [*Kameda et al.*, 2003]. (d) Na^+ concentrations measured in July 2001. (e) Pinaceae (black line) and *Artemisia* (shaded line) pollen concentrations measured in July 2001. The depths of the $\delta^{18}O$ profiles in 2000 are adjusted to the depth scale in 2001 on the basis of the 2000 and 2001 physical stratigraphy. SL marks the ice in the summer layer.

Range within the Russian Altai Mountains, situated in the border region between Russia and Mongolia (Figure 1). The major types of vegetation surrounding the range are tundra and steppe, including *Artemisia* and coniferous forest with *Pinus*, *Picea*, and *Abies*, as shown in Figure 1. The tree lines on the south and north facing slope around Sofiyskiy glacier are both about 2500 m asl, and tundra predominates above the tree line.

[5] In July of 2001 a 25.1-m-deep ice core was recovered on the accumulation area of Sofiyskiy glacier (3435 m asl), and a 4.5-m-deep pit was excavated about 50 m northwest of the drill site (Figure 2). In July 2000 a 3-m-deep pit was dug near the drill site [*Fujii et al.*, 2000; *Kameda et al.*, 2003]. At the drill site, some surface melting occurs during the summer season, and the firn temperature rises to 0°C [*Fujii et al.*, 2002]. Sofiyskiy glacier, like other Altai glaciers, is characterized as a summer-accumulation-type glacier [*Fujita et al.*, 2004; *Smedt and Pattyn*, 2004; *Pattyn et al.*, 2004]. The core samples were cut at intervals of about 20 cm, and pit samples were obtained every 10 cm. We analyzed all pit samples and core samples down to 18.60 m depth for pollen concentrations, oxygen isotope ratios ($\delta^{18}O$), and chemical concentrations. For the pollen analysis, 10 mL of water sample was filtered through hydrophilic PTFE membrane filters with a pore size of 0.2 μm, and pollen grains on the filters were counted using a microscope. No chemical treating was done for the pollen analyses. Total pollen counts in the samples ranged from 0 to 209 grains.

3. Results and Discussion

[6] The results of the pit samples are shown in Figure 3. By comparing the stratigraphy of the snow pits excavated in 2000 and 2001, the surface layer in July 2000 was identified near the 2 m depth in July 2001. Therefore the net balance between July 2000 and the following July can be estimated to be around 2 m in snow depth. This value is consistent with the 1.78 m that we measured using a fixed stake from July 2000 through July 2001.

[7] The vertical $\delta^{18}O$ profile in the 4.5-m-deep pit of 2001 has three peaks. Each maximum peak occurs near the summer season, as seen by comparison to the stratigraphy, and thus the 4.5 m pit includes 2 full years of snow accumulation. According to the peaks in the $\delta^{18}O$, the net balance during 2000–2001 is about 2.25 m in snow depth.

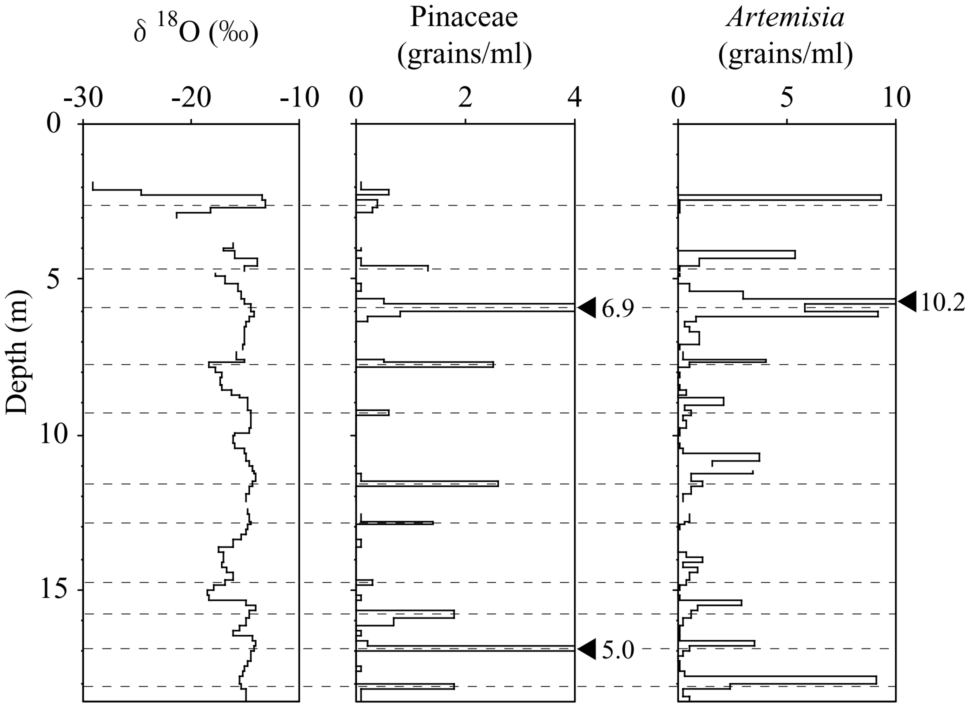

Figure 4. Oxygen isotope ratios ($\delta^{18}O$) and pollen (Pinaceae and *Artemisia*) concentrations from the 2001 Sofiyskiy glacier core. The dotted lines indicate annual boundaries estimated from Pinaceae pollen peaks. The upper 2 m and some parts of the core were not analyzed due to broken samples.

This value is close to the 2 m estimated from comparison of stratigraphy in the 2000 and 2001 snow pits. However, the amplitude of $\delta^{18}O$ for 1999 and 2000 is smaller in July 2001 (Figure 3b) than it was in July 2000 (Figure 3c). The records of major ion concentrations show that the peaks had disappeared rapidly; as an example, we show the Na^+ concentrations in Figure 3d. The Na^+ peaks in 1999 and 2000 are unclear, although the peak in 2001 is at the surface to 0.10 m depth. Thus chemical ion species cannot be used more deeply in the core.

[8] Pollen analyses of the pit samples showed that the most abundant pollen were Pinaceae (*Pinus*, *Picea*, and *Abies*) and *Artemisia*. In general, pollen grains of Pinaceae are scattered from late spring to early summer, whereas those of *Artemisia* are scattered in early autumn. Pinaceae peaks occur at 0.10–0.20, 2.40–2.50, and 4.30–4.40 m depths, while *Artemisia* peaks are about 20–30 cm above the Pinaceae peaks (Figure 3e). Moreover, the Pinaceae peaks are very close to the $\delta^{18}O$ peaks. These peaks correspond to the seasons of pollen dispersion; in particular, Pinaceae peaks mark spring, whereas *Artemisia* marks autumn. Therefore the peaks can mark both annual and seasonal layers. These pit observations show that even though chemical species and $\delta^{18}O$ profiles are significantly altered by postdepositional processes, pollen profiles in the same location are only weakly influenced by percolation and refreezing of meltwater.

[9] Figure 4 shows pollen concentrations and $\delta^{18}O$ in the firn core (for the stratigraphy, see *Kameda et al.* [2004, Figure 4]). Annual boundaries on the plots are marked from Pinaceae peaks. The small peaks of 0.1 grains mL^{-1}, for example, 5.2, 13.5, and 15.2 m depth in Pinaceae, are omitted because there are extra peaks of 0.1 grains mL^{-1} even during nonpollen seasons from the 4.5 m pit observation. If no *Artemisia* peak appears between two Pinaceae peaks, the Pinaceae peaks are accepted as the peaks from the same year because of the different seasons of pollen deposition. The same method is used to detect annual *Artemisia* peaks. Although the $\delta^{18}O$ peak in 2000 is clear, subsequent annual $\delta^{18}O$ peaks are weaker, presumably due to the mixing of $\delta^{18}O$ values from meltwater incursion. However, the pollen profiles show that the alternate Pinaceae-rich and *Artemisia*-rich layers remain strong. Compared to the profiles of $\delta^{18}O$, all Pinaceae peaks, except for the 1990 peak (at 18 m), are adjacent to layers that contained maxima in $\delta^{18}O$. The good agreement between $\delta^{18}O$ peaks and pollen peaks indicates that pollen dating is accurate. Moreover, all *Artemisia* peaks in the core are above the Pinaceae peaks (about 90–10 cm) as well as the pit profiles. All of this amounts to saying that the firn between Pinaceae and *Artemisia* pollen peaks from the same year is the summer layer. These findings provide evidence that pollen is a good marker of annual and seasonal layers, even for ice cores obtained from lower-latitude glaciers with significant melting. In addition, if the meltwater process, such as meltwater percolation and subsequent refreezing lower down, was revealed, reconstruction of annual net balances and summer balances from these annual and summer layers would be possible.

4. Conclusion

[10] Previous studies of ice cores in lower-latitude glaciers were generally limited to high-elevation glaciers without melting [*Thompson et al.*, 1985, 1995a, 1995b, 2000, 2002] because low-elevation, lower-latitude glaciers

have significant summer melting that complicates standard chemical analysis methods. However, such glaciers can contain relatively large amounts of pollen that can be analyzed to determine past climate condition. For example, we found that only 10 mL of melted water sample was needed for pollen analysis of one such glacier, Sofiyskiy glacier of the Russia Altai Mountains, which contrasts with previous studies that needed more than 1 L. Moreover, finding concentration peaks of the each pollen species is rather easy because these distinct peaks appear at different depths, depending on species that have different pollen seasons.

[11] Consequently, we have shown here that pollen analysis can be used to determine annual layers, even for an ice core obtained from glaciers with significant melting. Furthermore, this method also can be used to separate seasonal boundaries by using different pollen species.

[12] The lower-latitude glaciers where summer melting occurs have seldom received attention for ice core study up to date. Thus the analysis of pollen in such glaciers may provide a greater understanding of past climates in the lower latitudes.

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S. M. Arkhipov, Institute of Geography, Russian Academy of Sciences, Staromonetniy lane 29, Moscow 109017, Russian Federation. (arhipov@1system.ru)

Y. Fujii and M. Kohno, National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, 173-8515 Tokyo, Japan. (fujii@pmg.nipr.ac.jp; mkohno@pmg.nipr.ac.jp)

T. Fujiki and K. Fujita, Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, 464-8601 Nagoya, Japan. (fujikky@geobio.eps.nagoya-u.ac.jp; cozy@ihas.nagoya-u.ac.jp)

T. Kameda, Kitami Institute of Technology, 165, Koen-cho, Kitami, 090-8507 Hokkaido, Japan. (kameda@mail.kitami-it.ac.jp)

F. Nakazawa, Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, 464-8601 Nagoya, Japan. (nakazawa@ihas.nagoya-u.ac.jp)

K. Suzuki, Department of Environmental Sciences, Faculty of Science, Shinshu University, 3-1-1, Asahi, Matsumoto, 390-8621 Nagano, Japan. (kei@gipac.shinshu-u.ac.jp)

J. Uetake, Faculty of Bioscience and Biotechnology, Tokyo Institute of Technology, Ookayama, Meguro-ku, 152-8551 Tokyo, Japan. (juetake@bio.titech.ac.jp)