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First report of ice core analyses and borehole temperatures on the highest icefield on western Spitsbergen in 1992

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Abstract

Two ice cores (83.92 m and 24.41 m depth) were obtained at one of the highest areas (Snφ fjellafonna) in the western part of Spitsbergen in Svalbard by the Japanese Arctic Glaciological Expedition, 1992, with cooperation from the Norwegian Polar Research Institute. Firn layers were observed in ice cores from the surface to 30 m depth; these layers gradually densified and turned to ice below that depth. Refreezing ice layers were observed from the surface to the bottom of ice cores ; these layers were originally formed by refreezing of melt water in firn layers near the surface of the icefield. In the electrical conductivity profile of ice cores, peaks at two depths (18 m, 34.5 m) were well identified. The ice temperatures in the 24.41 m borehole ranged from −3.36 °C to −0.75 °C. The ice temperatures in the 83.92 m borehole ranged from −1.47 °C to 0.00 °C. Subnurface water was found below 21.46 m depth in the 24.41 m borehole. After 18 liters of water was drained from the 24. 41 m borehole, the rate of rise of water level in the borehole was observed.

1. Introduction

Ice coring, in-situ ice core analyses, borehole temperature measurements and meteorological observations were carried out in the western part of Spitsbergen in Svalbard by the Japanese Arctic Glaciological Expedition, 1992 (JAGE'92 in Svalbard), with cooperation from the Norwegian Polar Research Institute (Norsk Polarinstitutt). The overall objective of the JAGE is to study the climatic and environmental changes of the last several hundred years in the Arctic region (Watanabe and Fujii, 1988 ; Watanabe and Fujii, 1990 ; Watanabe *et al.*, 1931).

The primary objective of JAGE'92 in Svalbard was to clarify these changes in the western part of Spitsbergen, and to compare with the analytical results of Hφghetta ice core which was obtained in the northeastern part of Spitsbergen in 1987 (Takahashi *et al.*, 1993). The analytical results of the Hφghetta ice core have already been published (Kameda *et al.*, 1989 ; Fujii *et al.*, 1990 ; Kamiyama *et al.*, 1990 ; Kawamura *et al.*, 1991 ; Suzuki *et al.*, 1991 ; Suzuki and Fujii, 1992).

Field research was carried out at Snφfjellafonna (Fig. 1) from 23 July to 16 August, 1992. The icefield is located in one of the highest areas in North-western Spitsbergen. Ice cores were obtained at Site-A (79° 08'10"N, 13°17'30"E ; 1190 m a.s.l.) and Site-B (79°08' 10"N, 13°19'00"E ; 1160 m a.s.l.). Site-A was located on a saddle point and Site-B was on a flat area 30 m lower than Site-A. The distance between these two sites was 530 m. The coring depths at both sites were 83.92 m and 24.41 m, respectively. The sites were selected for the following reasons (Takahashi *et al.*, 1993) ;

(1) They are at high altitude, which means less

snow melt so that ice core dating is easier.

(2) This is a typical maritime icefield in Spitsbergen.

(3) Access by helicopter is easy (about 40 km north east from Ny-Ålesund).

The research area is about 8 km east from the point where Drs. H.W. Ahlmann, H.U. Sverdrup and

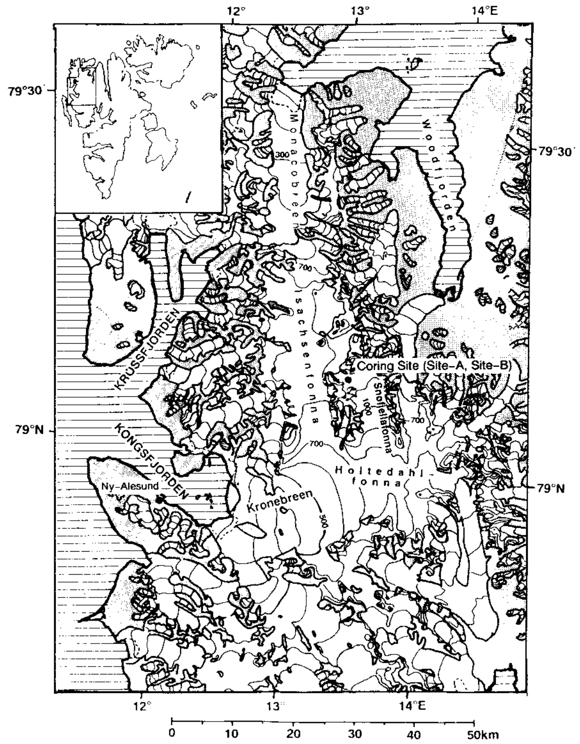

Fig. 1. Location of research area (Snøfjelafonna) and coring site (Site-A and Site-B) in the western part of Spitsbergen.

co-workers examined snow stratigraphy, temperature variations in the snow layers, and meteorological conditions on the icefield during the 1934 summer season (Ahlmann, 1935a). They found that alternate layers of firn and ice continued from the surface to 14.7 m depth, and the annual accumulation rate was estimated to be 200 mm/year in water equivalent (average value from 1899 to 1934) at their main camp on Isachsenfonna (79°09'N, 12°56'E ; 850 m a.s.l.) (Ahlmann, 1935b). They also found that firn temperatures at the main camp were 0.0 °C from the surface to 6 m depth at the end of July, 1934 (Sverdrup, 1935).

A Norwegian-French group has studied annual accumulation rates and ice temperatures on the glaciers in the western part of Spitsbergen since 1989. Annual accumulation rates were estimated at 19 sites and ice temperatures were measured at 13 sites (Lefauconnier *et al.*, in press). The group obtained two ice cores (24 m and 15 m depth) in the Snøfjellafonna region during April, 1992.

In this paper we will report our ice coring system and results of in-situ ice core analyses (density, electrical conductivity) of the Site-A ice core. Results of borehole temperatures in the two boreholes and observations of subsurface water in the Site-B borehole will be also reported.

2. Methods

2.1. Ice coring

A shallow type electro-mechanical drill (type MD-130S, Geo Tec Co. Ltd.) and a winch system (type W-MDS, Geo Tec Co. Ltd.) were used for our coring. Only two persons are needed to operate the whole coring system. Weights of the drill and the winch system are 25 kg and 110 kg, respectively. The length of the drill is 1.7 m and the length of the wire in the winch system is 120 m. A 0.4 m length of ice-core with a diameter of 78 mm was regularly obtained in each ice coring operation. Each ice coring operation consists of the following four stages : 1. checks and preparations of the drill and the winch system, 2. placing the drill into the borehole until the coring depth is reached, 3. ice coring, and 4. pulling the drill with ice core up. It took about 10 minutes to obtain an ice core for each ice coring operation at a depth of 10 m and about 20 minutes at 80 m, on average. The difference mainly comes from the difference of the travel time of the drill in the borehole (stages 2 and 4).

A 3.0 kW generator (type EM3000, Honda Co. Inc.) was used for the entire ice coring operation. The motors of the drill and winch system were 0.45 kW and 0.54 kW, respectively. Another 1.5 kW generator (type EC1500X, Honda Co. Inc.) was used for ice core analyses.

A 24.41 m ice core was obtained at Site-B in 5 days (from 29 July to 2 August, 1992) and an 83.92 m ice core was obtained at Site-A in 11 days (from 4 August to 14 August, 1992). As subsurface water came into the borehole at Site-B, we could not continue our coring at Site-B.

2.2. In-situ ice core analyses

After ice cores were obtained, the cores were stored in a core-processing cave. The core-processing cave was located adjacent to Site-B ; the floor level was 2.1 m lower than the snow surface (Takahashi *et al.*, 1993). The room temperatures varied from −10 °C to −1 °C. Ice cores were examined in detail by transmitted fluorescent illumination on a light table.

Shapes of air bubbles and positions of ice layers were recorded true to scale on a narrow roll of graph paper which was placed adjacent to the core. After the examinations of ice cores, weights of ice cores were measured with an electrical balance (type EL-6000, Shimadzu Co. Ltd.) at ±1 g resolution. Diameters of ice cores were measured by a caliper at ±0.1 mm resolution. In our original core-processing plan ice core cutting would be done in the core-processing cave during our stay on the icefield. However, whole ice cores were transported to a cold room in Ny-Ålesund by helicopter since the cave temperature was relatively high (−10.0 °C to −1.0 °C).

Temperatures in the cold room at Ny-Ålesund varied from about −20 °C to −15 °C. In the cold room ice cores were cut at an interval of 15 cm ; the samples were packed double into plastic bags (thickness : 0.05 mm) in order to minimize contamination of ice samples. The plastic bags are contamination-free (Goto-Azuma *et al.*, 1993).

Ice samples in the plastic bags were slowly melted at the room temperature (10 °C to 15 °C) at the NIPR station in Ny-Ålesund. The melted water was packed into contamination-free polypropylene bottles for detailed chemical and biological analyses in Japan. The electrical conductivity (EC) of the melted water (near 0 °C) was measured by an electrical conductivity meter (type SC-82, Yokogawa Electric Co. Ltd.) with a sensor for pure water (type SC-82). EC values measured by this system were automatically corrected to EC values at 25 °C.

2.3. Borehole temperatures

After ice coring at Site-A and Site-B, borehole temperatures were measured by a direct contact thermistor sensor system (Fig. 2). The thermistor sensor (model BYE-64, TECHNOL SEVEN Co. Ltd.) was placed in direct contact with the wall of the borehole by leaf springs. The system was connected to the drilling cable directly.

The resistance of the thermistor sensor (1.5066×10^4 Ω at 0.00 °C) with the drilling cable (8.962 Ω at −1.1 °C) was measured by a digital multimeter (SC7403, IWATSU Co. Ltd.) with a resolution of 1 Ω. Temperature dependence of the resistance of the drilling cable was negligible.

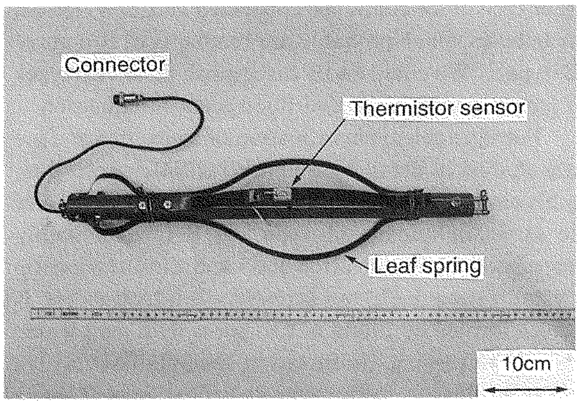

Fig. 2. The thermistor sensor system for borehole ice temperature measurements.

Calibrations of the thermistor sensor were carried out using a Pt 100 Ω temperature measuring system (Type F-25, Automatic System Laboratories) beforehand in the cold room at Kitami Institute of Technology, Japan. The absolute accuracy of the Pt 100 Ω system was ±0.03 °C (Measurements Service Division, CHINO CORPORATION Technical Center). The following equation which relates the thermistor resistance (R kΩ) to thermistor temperature (T K) was obtained by the method of least squares using 49 calibration points from −20.91 °C to 11.32 °C.

$$T(K) = \frac{3312.1021}{\mathrm{Ln}\ R(k\Omega) + 9.413146} \quad \cdots\cdots (1)$$

The correlation coefficient of the relationship was 0.9999 and the standard deviation of estimated temperature was 0.003 °C. Therefore, the accuracy and the resolution of the thermistor sensor was ±0.03 °C and ±0.003 °C, respectively.

3. Results and discussion

3.1. Stratigraphical observations and density profile of the Site-A ice core

Ice cores consisted of firn and ice in the upper part. Firn layers became glacier ice in the deeper part. Observed ice in the ice cores was divided into two types according to the amount and configuration of bubble inclusions : one type of ice contained less air bubbles, thus looking transparent (T-type). The other type of ice contained connected and/or spherical air bubbles which probably are remnants of firn pores (B-type). We could easily distinguish these two types of ice through transmitted fluorescent illumination.

Petrographical classification of snow, firn and ice was studied in detail by Shumskii (1964). According to his classification, the two observed types of glacier ice at Snøfjellafonna (T-type and B-type) probably correspond to "infiltration ice" and "infiltration-recrystallization ice", respectively. Infiltration ice is the ice formed by filling of firn pores with melt water and its refreezing. Infiltration-recrystallization ice is ice formed by infiltration densification and grain growth, settling and paratectonic crystallization. These descriptions and definitions come from Shmuskii (1964). Shumskii (1964) also wrote that "the complex, branching air bubbles, which are isolated remnants of firn pores are the most characteristic feature of infiltration-recrystallization ice".

The formation process of these two types of ice was not discussed quantitatively in Shumskii (1964) ; however, he pointed out that "the governing factor of the ice types is the relationship between the intensity of summer melting, winter freezing and the amount of solid precipitation deposited". Thus, the vertical distribution of these ice types is probably related to past climatic conditions at Snøfjellafonna. This point will be discussed in a separate paper.

A density profile of the Site-A ice core is shown in Fig. 3. As the Site-A ice core consisted of firn layers, infiltration ice, and infiltration-recrystallization ice, the density profile of the Site-A ice core was influenced by the densification processes of firn layer and infiltration-recrystallization ice, and also by the percentages of the above three types of firn and ice in the ice core.

The variations of density are relatively large from the surface to about 30 m depth and smaller below 30 m depth. This indicates that firn layers become glacier ice below about 30 m depth. Such a transition depth was also observed at about 30 m on other glaciers including Vallee Balache in France (Valoon *et al.*, 1976), Jostedalsbreen in Norway (Kawamura *et al.*, 1989), Yala Glacier (Dakpatsen Glacier) in Nepal (Iida *et al.*, 1984) and San Rafael Glacier in Patagonia, Chile (Yamada, 1987). The 30 m depth is probably determined by the densification parameters (load pressure and temperature) of temperate snow.

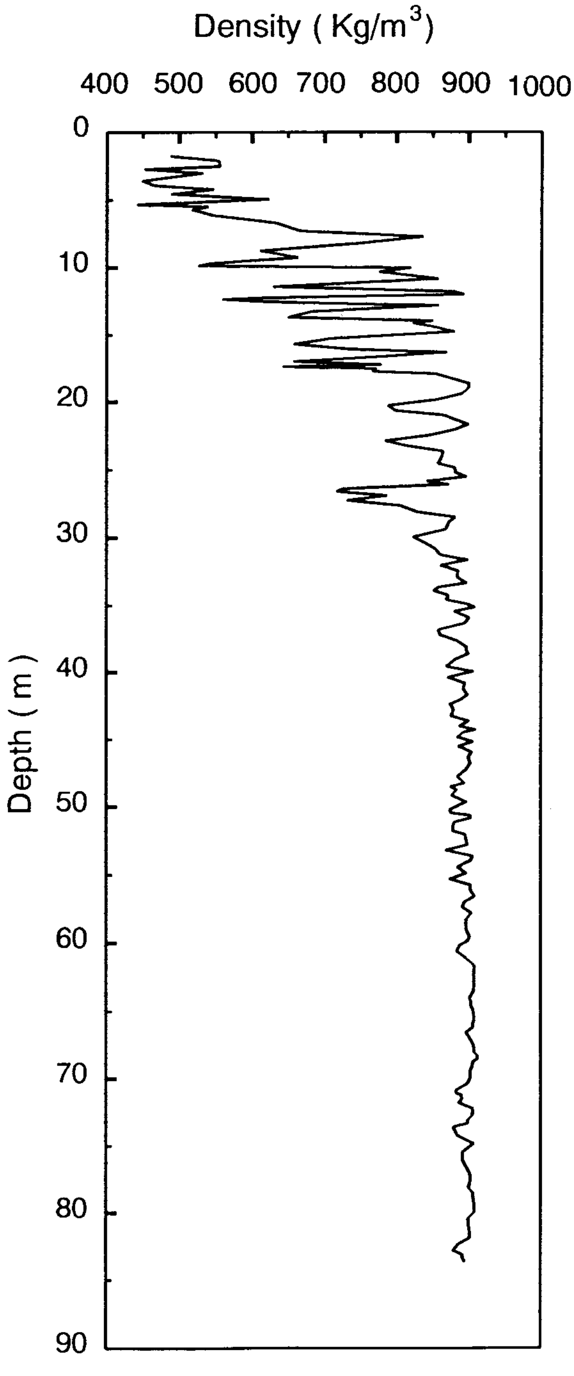

Fig. 3. Density profile of Site-A ice core.

3.2. Electrical conductivity profile of the Site - A core

The profile of electrical conductivity (EC) of the Site-A ice core is shown in Fig. 4. While the Site-A ice core has a length of 83.92 m, the EC measurements were done from the surface to 44.14 m during the 1992 summer season. Two peaks indicated with asterisks (*) are well identified in the profile. The peak at 34.50 m depth shows the highest value of EC. The peak around 18 m depth shows the second highest value of EC. The shape of this peak is broader than that of the highest peak at 34.50 m depth. We will measure tritium and ^{210}Pb concentrations of the Site-A ice core for dating. The EC profile presented in this paper should be interpreted together with the dating results.

3.3. Borehole temperatures

Measurements of ice temperatures in the Site-A borehole were started from 6 hours after ice coring operations were finished. For the Site-B borehole, measurements of ice temperatures were started from 23 hours after ice coring operations were finished. Measured thermistor resistances were converted to temperatures using equation (1). The temperature profiles at the Site-A and Site-B boreholes are shown in Fig. 5. Before describing the characteristics of the profiles, accuracies of measured temperatures are discussed.

Accuracies of measured ice temperatures are determined mainly by two factors : 1. absolute accuracy of the thermistor sensor system ; 2. stabilizations of measured ice temperatures in the boreholes. The first factor was explained in section 2.3. The second factor is discussed below.

The ice temperature at each depth in the boreholes was measured from just after the temperature measuring system was set and continued for 10 minutes. After measurements of the ice temperature at each depth, the thermistor sensor system was moved downward in the borehole. Typical ice temperature variations during the 10 minutes in the Site-A borehole are shown in Fig. 6. As these temperature variations were mainly caused by initial temperature differences between the borehole ice and the thermistor sensor system, these variations varied essentially according to an equation of heat conduction. Thus, an exponential curve was selected for an extrapolation of the measured ice temperature data points in order to estimate a stabilized ice temperature (Ts).

The first examinations are made to estimate the

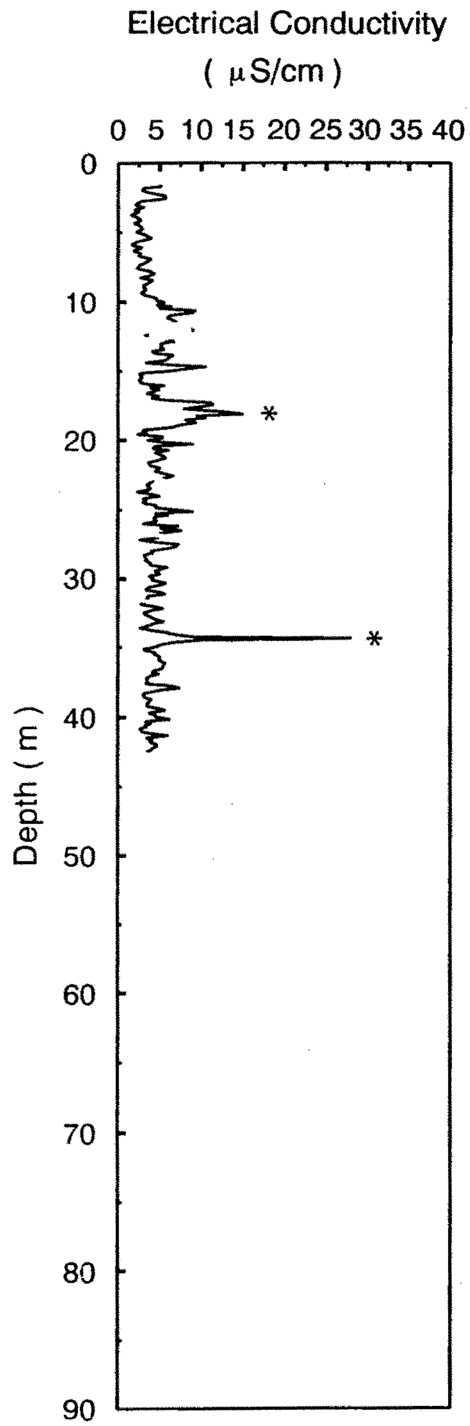

Fig. 4. Electrical conductivity profile of Site-A ice core. Two peaks indicated with asterisk (*) are well identified in the profile.

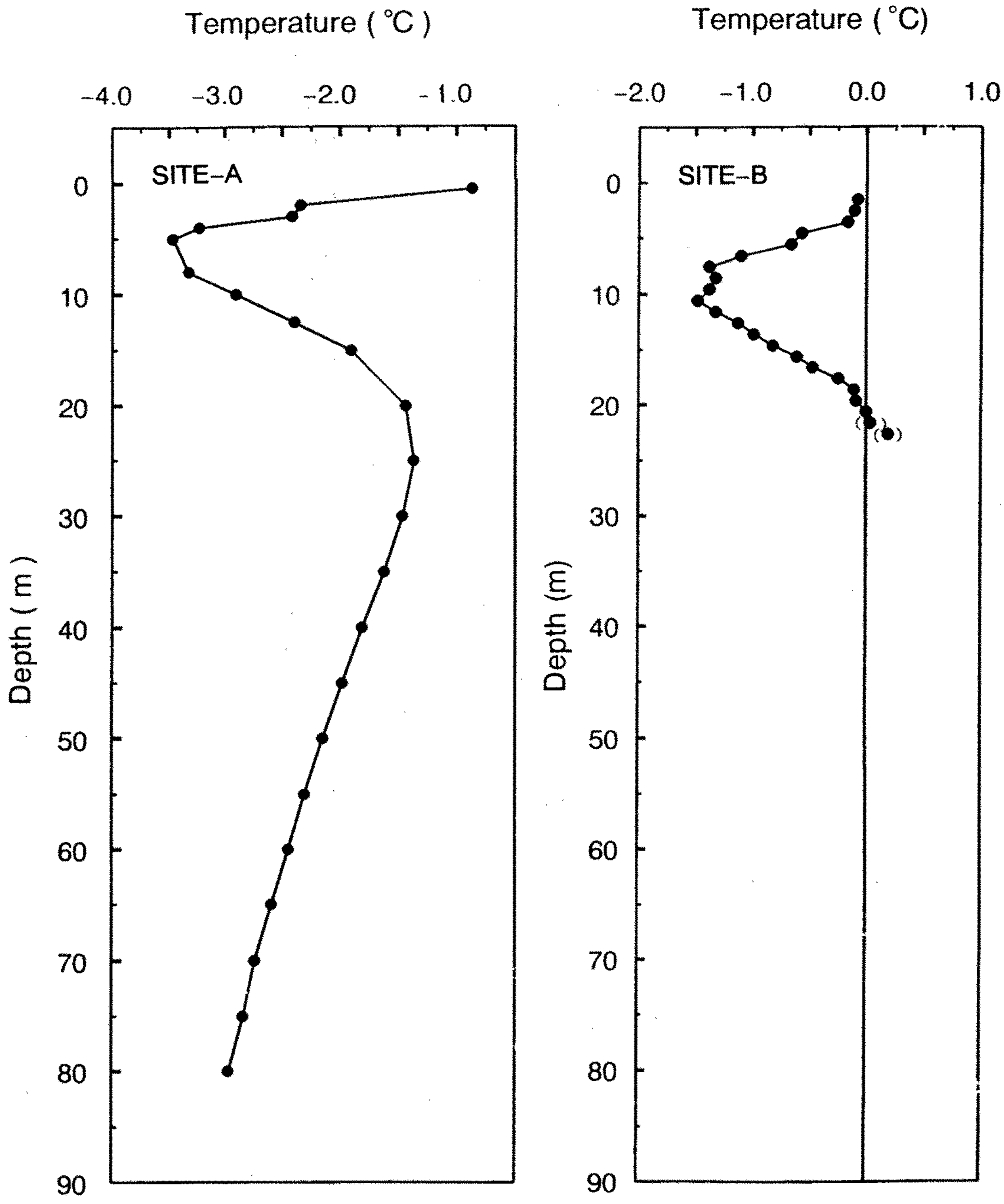

Fig. 5. Temperature profiles of Site-A and Site-B boreholes. The positive temperatures in the brackets in Site-B borehole correspond to subsurface water temperatures. The water was probably heated during ice coring in the water.

stabilized ice temperature (Ts) using ice temperature data points during the first 10 minutes at each depth. These data were obtained at 14 depth points in the Site-A borehole (5 m, 8 m, 15 m, 20 m, 25 m, 30 m, 40 m, 45 m, 50 m, 60 m, 65, 70 m, 75 m, and 80 m). An exponential curve was fitted for the ice temperature data for the first 10 minutes at each depth point by the method of least squares. Temperatures after the first 10 minutes (T10) and estimated stabilized ice temperatures (Ts) in the Site-A borehole are summarized in Table 1 for above mentioned depth. The mean difference between these two ice temperatures was 0.009 °C (±0.0045 °C).

The second examinations are made to estimate the accuracy of the stabilized ice temperature (Ts) as mentioned above. The measured ice temperature variation at a depth of 80 m in the Site-A borehole was used for this calibration because the thermistor sensor system was set at 80 m depth for 16 hours 26 minutes. Figure 7 shows two exponential curve fittings for the measured ice temperatures at 80 m depth ; an exponential curve (1) was obtained by the method of least squares using all data (13 data points) during the entire 16 hours 23 minutes, an exponential curve (2) was obtained by the same method using 11 data points during the first 10 minutes. It was found that two ice temperatures stabilized at −2.90 °C for a curve (1) and −2.87 °C for a curve (2), respectively. The difference between these two temperatures (0.03 °C) was caused by the difference in intervals for exponential curve fittings and the difference probably involved in other stabilized ice temperatures (Ts) in Table 1. Therefore, the accuracy of the Ts in Table 1 is probably on the order of ±0.06 °C because the absolute accuracy of the measuring system (±0.03 °C) must be added to the difference between the two stabilized ice temperatures (±0.03 °C).

On the other hand, initial ice temperatures and the temperatures after the first 10 minutes (T10) were only recorded for following depth points in the Site-A borehole : 0.5 m, 2 m, 3 m, 4 m, 35 m and 55 m, and for all depth points in the Site-B borehole. These data are summarized in Table 1 and Table 2, respectively. For the accuracy of the T10, the mean difference between the Ts and T10 (±0.0045 °C) must be added to ±0.06 °C. Therefore, the accuracy of the T10 is probably on the order of ±0.07 °C.

Estimated stabilized ice temperatures (Ts) at the 14 depth points as mentioned above and temperatures after the first 10 minutes (T10) at other depth points are used for Fig.5-(A). T10 are used for Fig. 5-(B).

Ice temperatures at Site-A were regularly measured at 5 m intervals. Additional points were measured from the surface to 15 m depth (0.5 m, 2 m, 3 m,

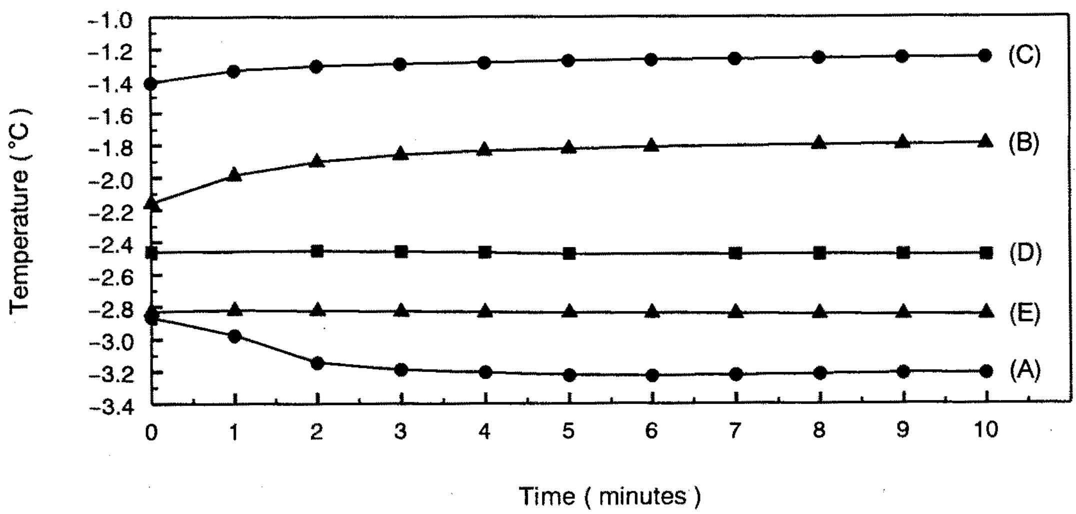

Fig. 6. Typical examples of measured ice temperature variations during the first 10 minutes in Site-A borehole. These variations were mainly caused by initial temperature differences between the borehole ice and the thermistor sensor system in the borehole. Ice temperatures at 8 m depth (A), 15 m depth(B), 45 m depth (C), 65 m depth (D), and 80 m depth (E) are shown.

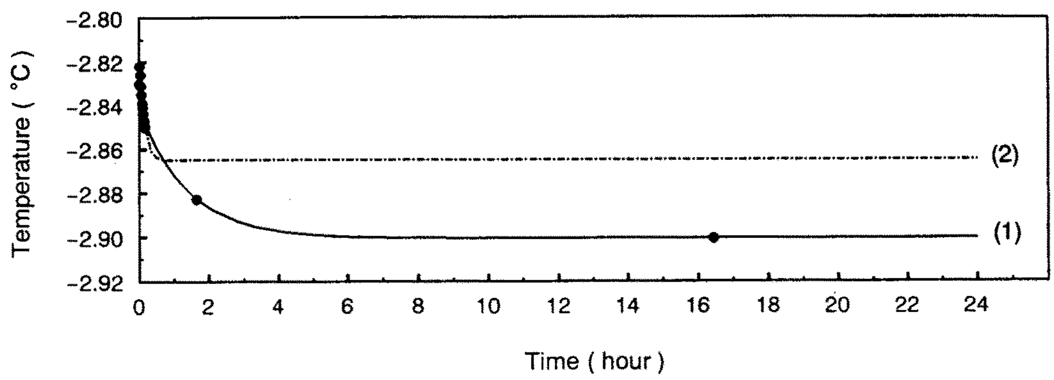

Fig. 7. Ice temperature variations at a depth of 80 m in the Site-A borehole. Time 0 was just after temperature measuring system was set at 80 m depth. Data points in this figure are the same as (E) in Fig. 6. Curve (1) was calculated from all data points (13 data points) during 16 hours 26 minutes by the method of least squares. Curve (2) was calculated from 11 data points during the first 10 minutes by the same method.

4 m, 8 m and 12.5 m). Ice temperatures rapidly decreased from the surface to 5 m depth, and reached a minimum (−3.36 °C) at 5 m depth as shown in Fig. 5-(A). From 5 m to 25 m depth ice temperatures rapidly increased and took a maximum value (−1.25 °C) at a depth of 25 m. Ice temperatures lower than 25 m depth gradually decreased again, to −2.87 °C at a depth of 80 m. It took about 20 hours to complete the 22 point ice temperature measurements in the Site-A borehole.

Ice temperatures at Site-B were regularly measured at 1 m intervals. Ice temperatures rapidly decreased from the surface to 10.6 m depth and reached a minimum (−1.47 °C) at 10.6 m depth as shown in Fig. 5-(B). Ice temperatures rapidly increased below 10.6 m depth, becoming 0.00 °C at 20.6 m depth. This ice temperature was probably caused by thin water layers on the borehole surface at the 20.6 m depth. Subsurface water was observed below 21.46 m depth. Thus, temperatures at 21.6 m (0.04 °C) and 22.6 m (0.20 °C) in depths correspond to the subsurface water temperatures. The subsurface water was probably heated during ice coring in the water. Thus, these data are expressed in brackets in Fig. 5 and Table 2. It took about 4 hours to complete the 22 point ice temperature measurements in the Site-B borehole.

While the elevation difference between the two sites is 30 m, ice temperature conditions were quite different between these two sites. The minimum ice temperatures at Site-A and Site-B boreholes were observed at 5 m and 10.6 m, respectively. These minimum ice temperatures had been formed by the penetration of winter cold waves in the previous winter and by penetrating warm waves during this past summer. The increase of ice temperature from 10.6 m to 20.6 m depth in the Site-B borehole was caused by subsurface water at 21.46 m in the icefield.

3.4. Subsurface water in the Site-B borehole

Subsurface water suddenly came into Site-B borehole (diameter : 102 mm) when the drill reached 22.12 m depth. The water level came up 0.66 m to a depth of 21.46 m. We continued our ice coring operation to a depth of 24.41 m. Because ice cores from 22.12 m to 24.41 m depth consisted entirely of ice, subsurface water accumulated in the borehole. The water level stayed at 21.46 m depth after the ice coring to a depth of 24.41 m.

The water level in the Site-B borehole was measured with a polypropylene bottle (250 cm^3) float connected to a tape measure (50 m in length). The resolutions of the measurements were ±1 mm.

Figure 8 shows the results of water level variations in the Site-B borehole. Time 0 refers to just after draining 18 liters of water from the borehole. It was found that the water level decreased by 12 cm by draining 18 liters of water. This lowering of water level in the Site-B borehole corresponds to a discharge of about 1 liter of water. Thus, it is obvious that water was supplied to the Site-B borehole from a water channel system in the icefield.

Table 1. Site-A borehole temperatures after the first 10 minutes at each depth (T10) and estimated stabilized ice temperatures (Ts). 10 minutes was counted just after the temperature measuring system was set in the borehole at each depth. Stabilized ice temperatures (Ts) were estimated by the method of least squares using ice temperature data points during the first 10 minutes. The estimated errors of the T10 and Ts are ±0.07°C and ±0.06°C, respectively.

Depth (m)	Temperatures after the first 10 minutes (T10) (°C)	Estimated stabilized ice temperatures (Ts) (°C)
0.5	−0.75	−
2.0	−2.23	−
3.0	−2.31	−
4.0	−3.11	−
5.0	−3.35	−3.36
8.0	−3.21	−3.27
10.0	−2.79	−
12.5	−2.28	−
15.0	−1.79	−1.79
20.0	−1.33	−1.32
25.0	−1.25	−1.25
30.0	−1.35	−1.35
35.0	−1.51	−
45.0	−1.87	−1.86
50.0	−2.04	−2.04
55.0	−2.19	−
60.0	−2.33	−2.34
65.0	−2.48	−2.48
70.0	−2.62	−2.63
75.0	−2.72	−2.76
80.0	−2.85	−2.87

After 18 liters of water was drained from the Site-B borehole, the water level came up 7 cm in 49 minutes. The average rate of rise of the water level during 49 minutes is 8.6 cm/hour. This rate corresponds to 700 cm^3/hour. The rising rate then decreased ; the average rate of the rise from 2 hours 45 minutes to 8 hours 48 minutes was 0.078 cm/hour which corresponds to 6.4 cm^3/hour. These observations indicate that the subsurface water in the Site-B borehole was connected to a water channel system in the icefield and water was supplied to keep a constant level at least in the summer season.

Table 2. Site-B borehole temperatures after the first 10 minutes (T10) at each depth. 10 minutes was counted just after the temperature measuring system was set in the borehole at each depth. The estimated errors of the T10 is ±0.07°C. The positive temperatures in the brakeks correspond to subsurface water tempesatures. The water was probably heated during ice coring in the water.

Depth (m)	Temperatures after the first 10 minutes (T10) (°C)
1.6	−0.07
2.6	−0.10
3.6	−0.16
4.6	−0.57
5.6	−0.66
6.6	−1.09
7.6	−1.38
8.6	−1.32
9.6	−1.37
10.6	−1.47
11.6	−1.32
12.6	−1.13
13.6	−0.99
14.6	−0.82
15.6	−0.61
16.6	−0.47
17.6	−0.24
18.6	−0.10
19.6	−0.08
20.6	0.00
21.6	(0.04)
22.6	(0.20)

4. Acknowledgments

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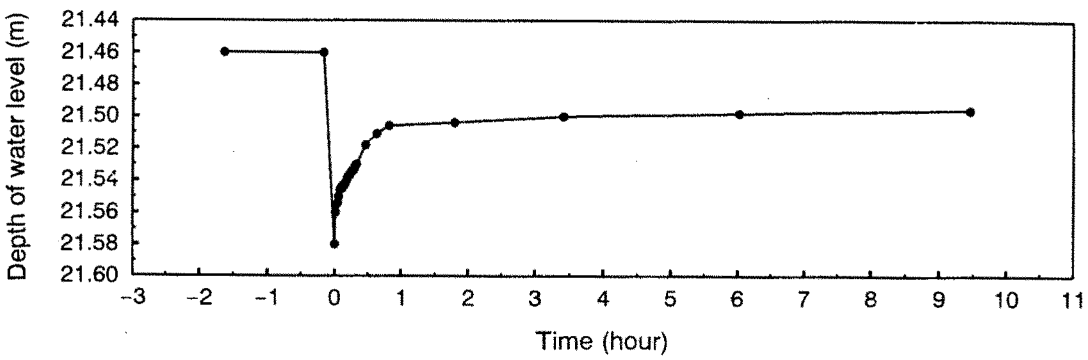

Fig. 8. Variations of water level depth in the Site-B borehole. Time 0 was just after the draining of 18 liters of water from the Site-B borehole.

and J. F. Pinglot were very helpful for determining our coring positions. Thanks are due to Drs. H. Ito, S. Ushio, and Mr. K. Furusawa of NIPR for their help for baggage transportation. Thanks are also due to Mr. F. Clark for his kind assistance in translation. This research has been supported by a Grant-in-Aid from Monbusho (the Ministry of Education, Science and Culture, Japan) International Scientific Program (No. 03041089).

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