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6000-YEAR CLIMATE RECORDS IN AN ICE CORE FROM THE HØGHETTA ICE DOME IN NORTHERN SPITSBERGEN

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ABSTRACT

In 1987 an ice core to the bedrock at a depth of 85.6 m was drilled at the top of Høghetta ice dome in northern Spitsbergen. Chronology of the ice core was examined by tritium and ^{14}C methods showing time gap at about 50 m depth. The age of three bottom ice samples was determined as 4150–5670 year B.P. by ^{14}C method done for frozen bacteria colonies and a frozen petal. This chronology and negative bottom temperature of −9.4°C suggest that glaciers in Spitsbergen shrank considerably during the hypsithermal. The pH of melt-water samples lower than 5.0 corresponds well to large northern hemispheric volcanic eruptions during the last 300 years. Increase of acidity from 30 m depth to the surface may reflect the spread of air pollution to the Arctic during the past 200 years. On the basis of ice-core analyses on electrical conductivity, pH, chemical composition and air bubble pattern, climate and environment in Spitsbergen during the last 6000 years are discussed.

INTRODUCTION

A recent global circulation model (GCM) indicates large-amplitude climatic variation in the marginal zone of the Arctic cryosphere because of the positive feedback effect of the extent of sea ice and snow cover on climate (Manabe and Stauffer, 1980). As Spitsbergen in the Arctic is located in the seasonal sea-ice zone, glaciers there are expected to preserve palaeoclimatic variation well. A Soviet glaciological team has been conducting a long-term ice-core drilling program in southern and central Spitsbergen and

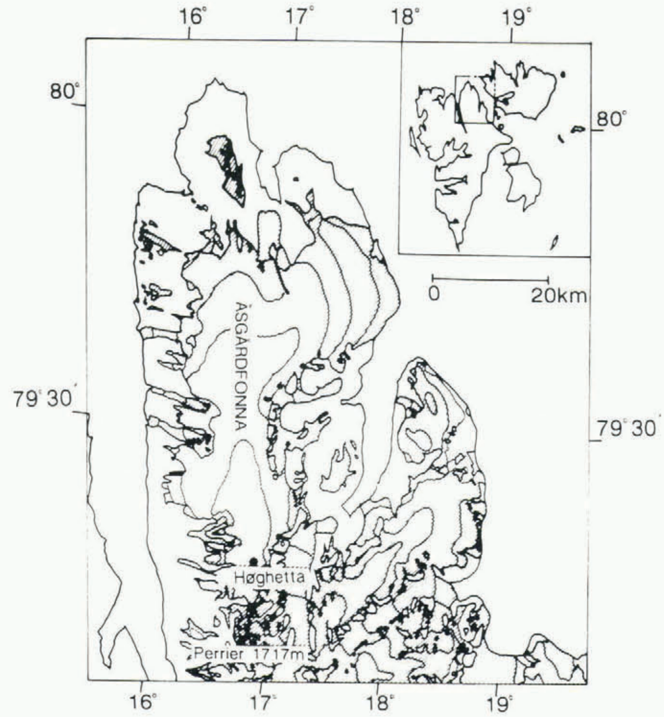

Fig. 1. Location of ice core drilling site shown by solid circle at Høghetta ice dome in northern Spitsbergen.

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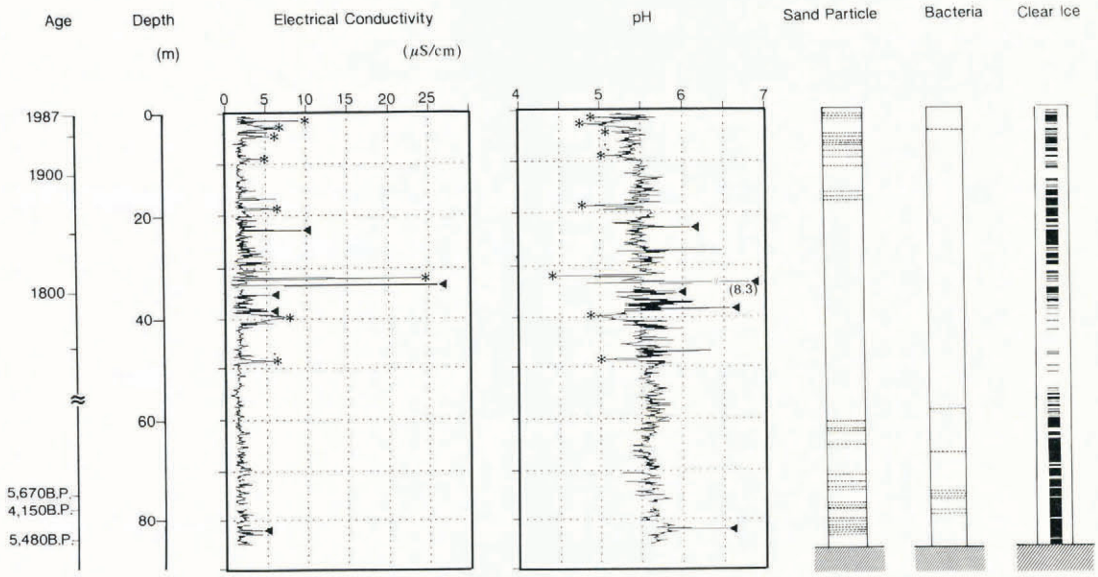

Fig. 2. Profiles of electrical conductivity, pH, layers with visible sand particles and bacteria colonies, with a suggested time scale. Asterisks and solid triangles, respectively, mark signals of electrical conductivity and pH corresponding to volcanic events and terrestrial salt-rich layers.

Nordaustlandet, Svalbard (Zagorodnov, 1988). However, no ice-core drilling has been done before in northern Spitsbergen where the firn line is located at the highest elevation in Svalbard (personal communication from Liestol) probably due to lower precipitation and development of superimposed ice.

We therefore planned ice-core drilling in northern Spitsbergen for the study of the palaeoclimate-environment system during the last thousand years.

FIELD WORK

Ice-core drilling was carried out at the top of an ice dome called Høghetta in northern Spitsbergen (16°50′ E, 79°17′ N, 1200 m a.s.l.; Fig. 1) with an electro-mechanical drill by the Japanese Arctic Glaciological Expedition (JAGE) from May to June 1987, as outlined by Watanabe and Fujii (1988).

Drilling reached a very hard layer at 85.61 m depth. Judging from the following evidence, the hard layer is thought to be bedrock: the drill could not penetrate further, blades of the drill were blunted, and small fragments of rock were collected in the grease oil applied to the cable head which was winched down to the hard surface.

Ice-core analyses *in situ* were carried out on the following items: stratigraphy, electrical conductivity, pH, density, ice fabrics, grain size, air bubble shape and total gas content. Some ice core and melt-water samples were transported to Japan and stored in a low-temperature room

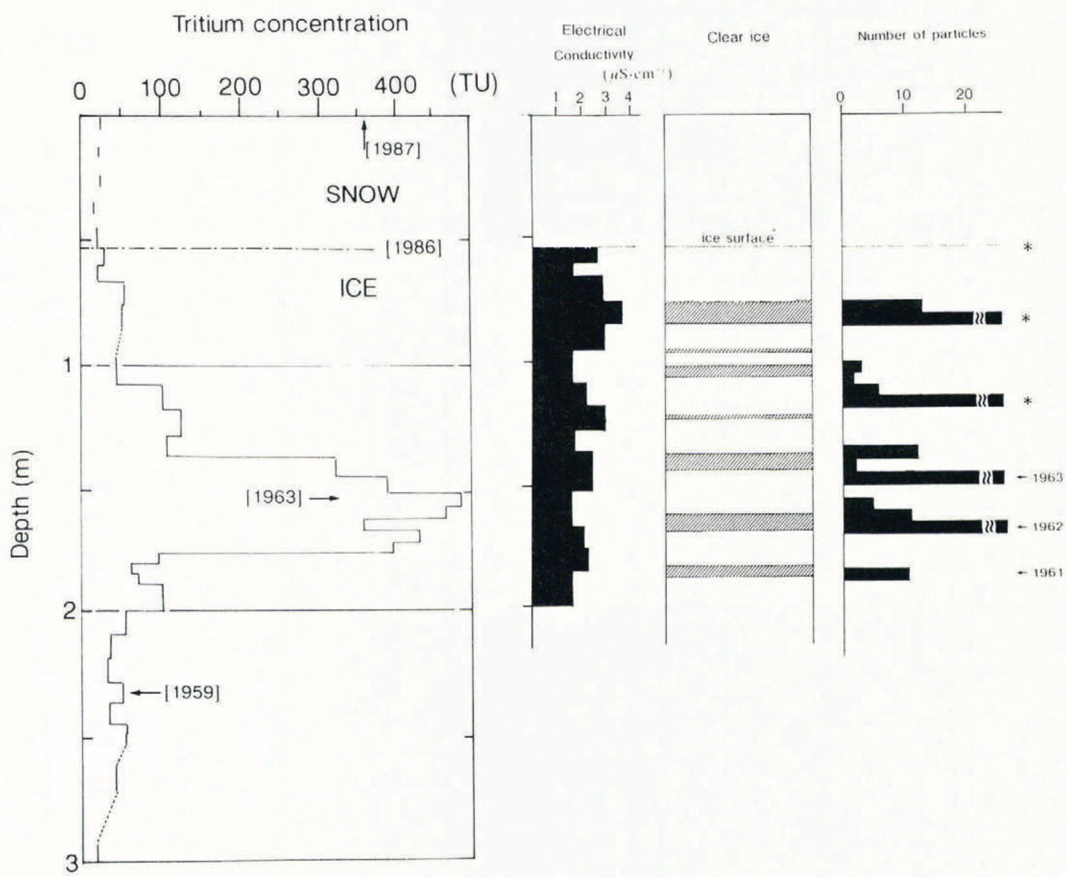

Fig. 3. Tritium content, electrical conductivity and stratigraphic features of the surface 3 m layer. Estimated years are shown in the figure. Asterisks indicate probable annual layer boundaries.

of the National Institute of Polar Research for the following analyses: chemical composition, tritium content, ^{210}Pb, ^{14}C, oxygen isotope ratio and others.

RESULTS AND DISCUSSION

The results of analyses for the whole core are shown in Figure 2, with a suggested time scale. Interpretation of the results is discussed below.

Core chronology

Tritium content and some surface stratigraphic features for the surface 3 m layer are shown in Figure 3. The top 0.54 m is snow deposited in winter 1986/87 and the layer below 0.54 m is superimposed ice, some with air bubbles. A significant peak at 1.6 m is thought to be the 1963 level, and a minor peak at 1.95 or 2.3 m depths below it indicates the 1959 horizon. According to the tritium profile at Dye-3, Greenland (Koide and others, 1982), a minimum in 1960 and 1961 from the moratorium on atmospheric nuclear tests was followed by a rapid increase from 1962. On the analogy of the tritium profile at Dye-3, the pre-moratorium peak in 1959 should be the peak at 2.3 m depth. This gives an average accumulation rate of about 20 cm of ice for the period between 1959 and 1963.

The periodic cycle of 20 cm is partly recognized in visible sand particle numbers, electrical conductivity and intervals of clear ice layers as shown in Figure 3. Furthermore, cobwebbed air bubbles develop with a thickness of about 20 cm below the ice surface at 0.54 m depth. The periodicity of 20 cm is therefore thought to be the predominant accumulation rate, though the mean rate is 4.7 cm of ice for the period from 1963 to 1986 (from tritium peak to ice surface), probably due to negative mass balance in some years during this period. The 20 cm ice is used for estimation of ice-core age before 1963 in this paper.

Judging from significant signals with both low pH and high electrical conductivity, major volcanic events are marked with asterisks in Figure 2. The ages of volcanic signals estimated with the above-mentioned accumulation rate correspond to volcanic events as shown in Table I.

Present chronology seems to be reasonable because the strong and prolonged acid signal at 39.7 m depth corresponds to the volcanic eruption of Laki in 1783, which caused the highest acid fallout since 1500 A.D. in the acidity record of ice cores from Greenland (Hammer and others, 1980).

^{14}C dating was adapted for small bacteria colonies found in ice core samples at 75.3 m and 85.2 m depths and for a petal frozen at 78.8 m depth, using the Tandetron Accelerator Mass Spectrometer at Nagoya University. We obtained the following results which indicate that the bottom ice has the age of 4150–5670 year B.P., generally considered to be hypsithermal. Age inversion with respect to the depositional sequence is found but the reason is not clear.

NUTA-670	75.3 m depth	5670 ± 100	year B.P. (bacteria)
NUTA-671	78.8 m depth	4150 ± 290	year B.P. (petal)
NUTA-698	85.2 m depth	5480 ± 400	year B.P. (bacteria)

TABLE I. DEPTHS, ESTIMATED AGES AND VOLCANIC EVENTS

Depth m	Estimated age	Corresponding volcanic events	
1.4	1963	1963:	Agung
4.6	1947	1947:	Hekla
9.0	1925	1912:	Katmai
19.5	1872	1883:	Krakatoa
31.8	1811	1815:	Tambora
39.7	1772	1783:	Laki
48.7	1727	1730–36:	Lanzarote

pH profile

In-situ measurement of pH was carried out continuously with a pH meter (HM-30S, TOA Electrics Ltd) for melt-water of ice samples cut into 10–20 cm intervals. Kamiyama and others (1989) divided the pH profile shown in Figure 2 into three fractions: the upper from the surface to about 20 m depth, the middle from about 20 m to about 50 m depth, and the lower from about 50 m depth to the base of the glacier. Variation of pH decreases below about 50 m depth, suggesting a time gap at this depth. These fractions are associated with climatic and environmental difference as discussed below.

The increase of acidity from about 30 m depth to the surface is clear in Figure 4, probably due to increase in acidity of precipitation in this region since the industrial revolution. The pollutant is presumed to be transported from civilized middle latitudes as indicated by measurements of SO_4^{2-} at Ny Ålesund in Spitsbergen (Iversen and Joranger, 1985).

Electrical conductivity

Electrical conductivity of melt-water was measured *in-situ* with a meter (CM-1K, TOA Electrics Ltd) fitted with a sensor for low conductivity (CV-1001SC, TOA Electrics Ltd). The profile of electrical conductivity (Kamiyama and others, 1989) is shown in Figure 2. The peaks exceed 5 $\mu S\ cm^{-1}$ concentrate between 17 and 48 m depths and are well correlated with both low and high pH events.

Peaks of high electrical conductivity at low pH shown with an asterisk in Figure 2 correspond to great volcanic eruptions, as mentioned above. On the other hand, peaks with high electrical conductivity and high pH, shown with solid triangles, probably contain terrestrial salts; a high content of Ca occurs in samples at the peaks. Particularly high electrical conductivities of 24 $\mu S\ cm^{-1}$ at 30 m depth and 26 $\mu S\ cm^{-1}$ at 32 m depth correspond to minimum and maximum pH. These suggest the frequent mass transportation of impurities to this region around 1800 A.D.

Sand particles

Sand particles were seen in clear ice from the surface to 20 m depth, and below 60 m depth to the glacier bed, as

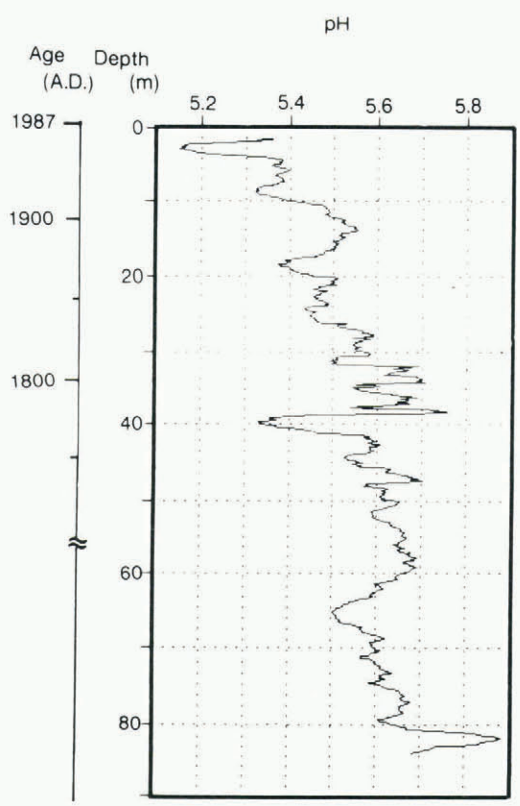

Fig. 4. Smoothed variation (20-point running mean) of pH of melt-water core samples, indicating increase of acidity since about 1800 A.D.

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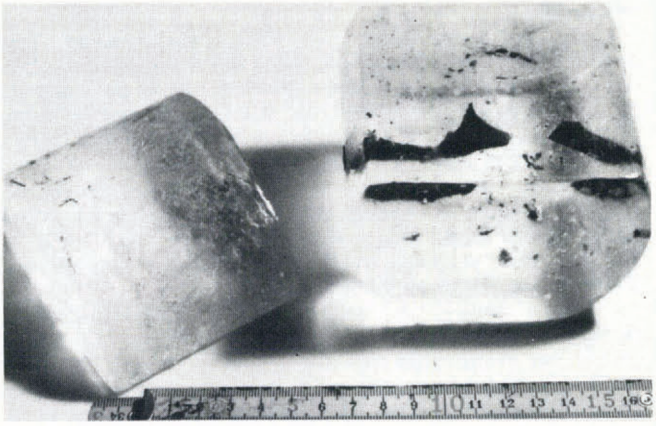

Fig. 5. Largest bacteria colony found frozen at 75.3 m depth. The ^{14}C age is 5670 ± 100 year B.P., during the hypsithermal.

shown on the left of Figure 2. As the particles are larger than 0.2–0.5 mm in diameter, they are thought to have been transported only short distances, from a local source.

This suggests that the environment during the hypsithermal and the period from 1880 A.D. to the present included: (1) a larger extent of snow-free area near the glacier, and/or (2) prevailing southerly winds where snow-free areas are located today.

Visible organic matter

Bacteria colonies were observed in ice at 4.9 m depth and frequently below 58.7 m depth to the glacier bed, as shown on the right of Figure 2; diameters range from a few mm to about 1 cm (Fig. 5). As these bacteria colonies grow in melt-water pools on glaciers, not in ice (Kohshima, 1989), supra-glacial ponds seem to have developed about 100 year B.P. and during the hypsithermal.

A petal 7 × 6 mm in size, frozen in at 74.8 m depth, had a ^{14}C age of 4150 ± 290 B.P. Existence of these organic substances suggests that it was warm, and therefore that the glacier was considerably thinner, during the hypsithermal.

Air bubble shape

Shapes and distribution of air bubbles were observed through the entire core and classified into five patterns (Kameda and others, 1989). Their distribution probably depends on climate, which affected the formation of air bubbles. Bubble-free clear ice, probably formed by freezing of a supra-glacial pond, was predominant below 60 m depth to the glacier bed, as shown in Figure 2. This formation of bubble-free ice corresponds to the warm climate during the hypsithermal. Bubble-free clear ice was rarely observed between 30 and 60 m depths. This suggests colder summers and/or higher snow accumulation during the period corresponding to those depths.

Bubble-layer type, which reflects the previous snow stratification, may have been formed by freezing of saturated snow with melt-water. This kind of air bubble developed between 5 and 15 m depths and 30 and 50 m depths.

Estimated palaeoclimate during the last 6000 years

The results obtained by ice-core analyses mentioned above are summarized in Table II. Estimated climatic conditions are outlined at the right of the table.

Very warm climate lasted from about 6000 B.P. to 4000 B.P. at least in northern Spitsbergen, judging from the existence of bacteria colonies and a petal frozen in ice below 60 m in depth, with the above-mentioned ^{14}C ages. As temperature at the bottom of the borehole is −9.4°C, subglacial melting is not likely to have occurred even during the hypsithermal. Thickness of ice at the top of the present ice dome is, therefore, thought to have been only 35 m, about one-third of the present thickness, during the hypsithermal.

After the hypsithermal, there seems to have been a time gap between about 4000 B.P. and 1700 A.D., probably due to negative mass balance of the glacier before about 1700 A.D. Climatic conditions during 1700 to 1880 A.D. in the Little Ice Age seem to have been cold and stormy. Absence of visual sand particles and organic material indicates long seasons of snow cover with no supra-glacial pond formation during the period. A less negative stable oxygen isotope ratio is shown in an ice core from Lomonsovfonna in central Spitsbergen during this period (Vaykmyae and others, 1985). The large variability of both pH and electrical conductivity during this period suggests stormy weather.

The period from 1880 to 1945 A.D. is characterized by a fluctuating warm–cold climate. After 1945 A.D., the climate has become warmer and a bit stormy.

CONCLUSION

The present study shows the possibility of reconstructing past climates and environments by analysing an ice core from a superimposed ice zone on an existing Arctic glacier. Further studies on stable oxygen isotope ratio, chemical composition including organic matter, and ^{210}Pb dating, would clarify and add detail to climate and environment during the last 6000 years.

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TABLE II. SUMMARY OF RESULTS OBTAINED BY ANALYSES OF AN ICE CORE FROM HØGHETTA, AND ESTIMATED CLIMATIC CONDITIONS DURING THE LAST 6000 YEARS.

Depth	Period	Variability		Sand	Organic matter	Clear ice	Bubble layer	Estimated climate
m		pH	EC					
0–5	1945–present	L	L	Y	Y	Y	N	warm
5–20	1880–1945 A.D.	S	S	Y	N	Y	Y	cold/warm
20–50	1770–1880 A.D.	LL	LL	N	N	Y/N	Y	cold and stormy
50–85	4000–6000 B.P.	S	S	Y	YY	YY	N	very warm

L: large, LL: very large, S: small.
Y: observed, YY: observed frequently, N: not observed.

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