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Ice core drilling at King Col, Mount Logan 2002

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Abstract

An ice core of 220.52 m was drilled at King Col (60°35' 20" N, 140°36' 15"W; 4135m), a saddle near Mount Logan (5959 m), the Canada's highest mountain, in order to better understand 1) anthropogenic impact on the Pacific sector of the Arctic, 2) decadal and interdecadal climate changes in the North Pacific, and 3) dynamical behavior of cold mountain glaciers. The thickness of the glacier was estimated by an ice-penetrating radar survey at five points and the drilling site was decided at the flattest surface of which depth was calculated as 222 m. The recovered ice cores showed the site was located at dry snow zone with a very limited amount of melt-freeze ice layers. Temperature of the borehole was −18.0 °C at 10 m-depth and −17.7 °C at 220.52 m. The *Nye time scale* suggested that the ice core covers approximately several hundreds years to a millennium record of past climate and atmospheric proxy signals, provided annual accumulation rates from 0.4 to 1.0 m a^{-1} in ice.

1. Introduction

Ice cores from mid- and low-latitudes mountains are now considered to be one of the most important archives recording time-series of proxy climate signals (*e.g.* Wagenbach, 1989; Thompson, 2000). Multiple ice cores were retrieved from the world mountains and provided various proxy climate time-series spanning from the Last Glacial to the 20^{th} century.

Among various ice cores, those obtained from mountains fringing the North Pacific are of particular interest because they are found to have recorded annual, decadal and interdecadal climate fluctuations which are difficult to reconstruct from lacustrine and marine sediments due mainly to their low time-resolutions. Holdsworth *et al.* (1992) and Holdsworth (2001) related the accumulation time-series of Mount Logan with Japanese precipitation. Moore *et al.* (2001) later interpreted this teleconnection as an extra-tropical response of ENSO to the higher latitude. While Shiraiwa and Yamaguchi (2002) attempted to compare the Logan accumulation-time series mentioned above with that obtained from Ushkovsky volcano, Kamchatka, and found that the two are anti-correlated with time-frequencies of 32.1, 12.2, 5.1, and 3.7 years. These studies suggested a possibility of climate system which is obviously see-sawing over the North Pacific. It is necessary to extract additional high time-resolution records to ensure this relationship for the last millennium time periods.

Our drilling program at Mount Logan was originally planed to clarify 1) anthropogenic impact on the Pacific sector of the Arctic, 2) decadal and interdecadal climate changes in the North Pacific, and 3) dynamical behavior of cold mountain glaciers. We decided to drill an ice core within the massif of Mount Logan (5959 m a.s.l.), the Canada's highest mountain, to extract records from planetary boundary layer which are thought to be located at much lower altitude than the previous drilling site at 5340 m (Holdsworth *et al.*, 1991; 1992). We will report here our field activities conducting the radio-echo soundings, shallow ice-core drilling, borehole thermometry, and installation of a strain net at King Col (60°35' 20" N, 140°36' 15"W; 4135 m) of Mount Logan. The overview of the whole project is reported by Goto-Azuma *et al.* (2003) and is not given here.

2. Geographical setting

The drilling and the related observations were conducted at King Col which was a saddle between Mount Logan and King Peak (5173 m) (Figs. 1 and 2). The site is located just north of the world-largest ice field, Bagley ice field and Seward Glacier complex. The King Col itself constitutes the highest point of Quintino Sella Glacier. It is nearly flat saddle confined by two icefalls, one from Mount Logan to the north and the other from Schoening ridge to the south. The ice in the saddle is mainly drained into Quintino Sella Glacier to the west, but part of the ice is collapsing from the big wall of Schoening ridge to the east.

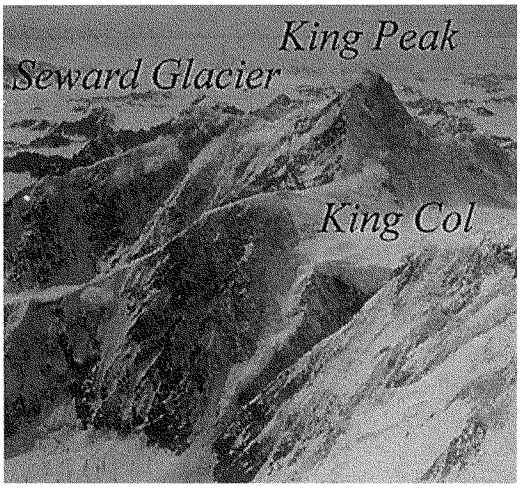

Fig. 1. Aerial view of the King Col (4135 m) taken from the helicopter near the summit of Mount Logan (5959 m). Piramidal peak behind the King Col is King Peak (5173 m).

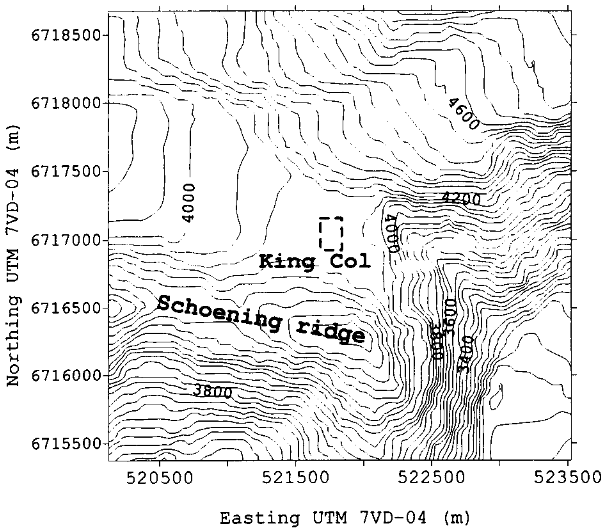

Fig. 2. Topographical map of the King Col region (contour interval: 50 m). Original digital elevation data was provided by Dr. Michael Demuth of Geological Survey of Canada. Dotted square at the central part of the King Col is surveyed more in detail as shown in Fig. 3.

Topographical survey of the micro relief at the King Col indicates that the flattest place is located between the two ridges from north and south of the col (Fig. 3). The surface of the King Col was covered with wind-eroded structures such as sastrugi and dunes with 0.1-0.2 m high when we first arrived at the King Col in April 30. It was flattened later in the beginning of May due mainly to snowfall. It became bumpy again in the middle of May but finally flattened by substantial amount of snowfall in the end of May. These changes in the snow surface are caused by accumulation and wind-erosion during the operation and it is best displayed in the record of snow stake network covering the central part of the King Col (Fig. 4).

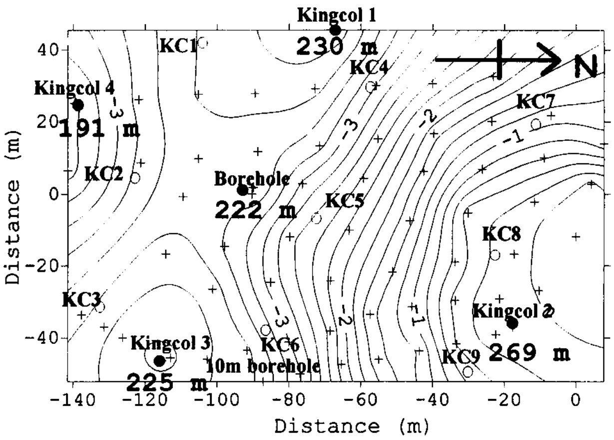

Fig. 3. Topographical map of the micro-relief at King Col (contour interval: 0.2 m). The contour line was drawn on the basis of our survey with the control point at the distances of (0, 0). Cross, open and solid dots indicate the surveyed points, snow stakes and the radar-echo sounding sites, respectively. Gothic 3 digit numbers indicate the thickness (m) of the ice sounded with the ice-penetrating radar.

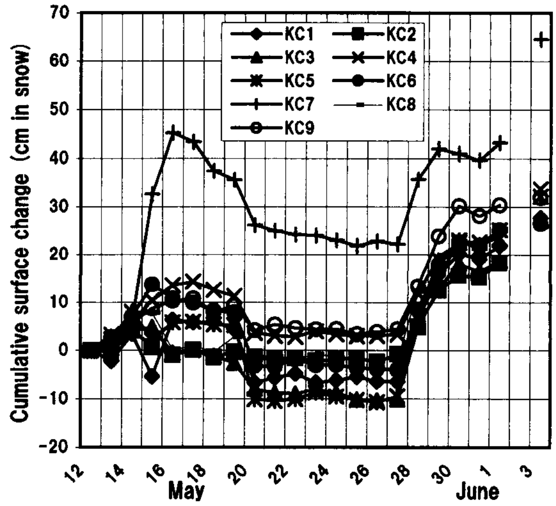

Fig. 4. Change of the snow surface during the drilling operation from May 12 to June 4. The stakes were installed inside the area shown in Fig. 3.

We did not monitor air temperature continuously. Intermittent temperature measurement and visual observation on the snow surface indicate that melting at snow surface was never observed during our stay at King Col from May 8 to June 12. Several pit observations were conducted at the places and all of the data indicate that the King Col is located at dry snow zone and summer melting is nearly zero or limited in time. One of the authors (Goto-Azuma) studied this site in the years of 2000 and 2001 and found that the accumulation rate at this site was highly variable from year to year, and the estimated accumulation rate by means of pit stratigraphy from 2001 to 2002 was 0.60 m a^{-1} in water (Goto-Azuma *et al.*, 2003).

3. Determination of the drilling site

The drilling site was decided in order to fill the following two requirements: 1) obtaining the oldest ice at the site and 2) recovering the ice which has experienced the simplest strain since its deposition. We have, therefore, selected one of the flattest place where we believed we could drill to the bottom by our drilling system.

Ice thickness was sounded by an ice-penetrating radar system. The system is composed of an impulse transmitter and a set of a transmission and a receiving antennas at the central frequency of 5 MHz. Time series of received voltage were digitized and stacked with a portable oscilloscope. 8-bit digitized values are acquired for a set of received signals in a personal computer.

The central part of the King Col was gridded with snow stakes by 50 m and the radio-echo soundings were conducted at 4 grids labeled as Kingcol 1, 2, 3, and 4 (Fig. 3). The central grid was also sounded with the most careful ways with so called common-mid point method, that is, changing the transmitting and receiving antennas separations with the fixed mid point. Also we changed the antenna orientation with every 45 degrees and obtained the received signals at four antenna orientations. Using these two ways, we confirmed that the received signals did not depend on antenna separations and orientations significantly. This means that the received signals were basically composed of reflected radio waves beneath the surveyed site and surrounding surface and subglacial peaks are not critical.

Figure 5 shows the time series of the radio waves at the five sites (a: Borehole; b: Kingcol 1; c: Kingcol 2; d: Kingcol 3; e: Kingcol 4 as shown in Fig. 3). Each of the waves was obtained with antenna separation of 30 m, but with different antenna orientations (a and b: east-west; c to e: north-south). The five waves showed clear reflections indicated by arrows at 2.48 (a), 2.57 (b), 3.01 (c), 2.52 (d), and 2.14 (e) μs, respectively. Considering the separation of the transmitting and the receiving antennas of 30 m, the thickness of the ice d can be calculated as follows (Matsuoka *et al.*, 1999);

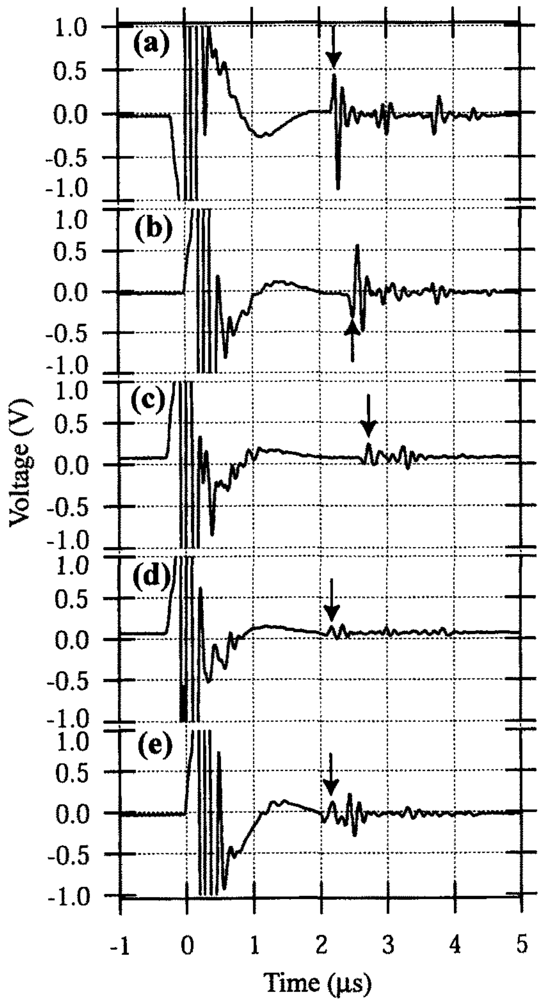

Fig. 5. Time series of received radio waves at five locations (a: Borehole; b: Kingcol 1; c: Kingcol 2; d: Kingcol 3; e: Kingcol 4 as shown in Fig. 3). Arrows indicate the reflection from the bedrock.

$$d=\sqrt{\left(\frac{\nu T}{2}\right)^2-L^2},$$

where ν (m μs^{-1}) is a velocity of the radio wave, T (μs) a delay time, $2L$ (m) the antenna separation distance. The average density of the glacier was calculated as 800 kg m^{-3} by the bulk density measurements of the ice core as mentioned below, so the radio wave velocity ν was calculated as 179 m μs^{-1} by using Looyenga's equation (Glen and Paren, 1975) and assuming the permittivity of pure ice at temperature of -18.5 °C as 3.17 (Mätzler and Wegmüller, 1987). The thickness of the glacier at the borehole was thus calculated as 222 m. The other four points were calculated as 230 m (Kingcol 1), 269 m (Kingcol 2), 225 m (Kingcol 3) and 191 m (Kingcol 4), respectively (Fig. 3). Because the length of our winch cable was 220 m at the maximum, we have selected the central part of the grid as our drilling site.

4. Ice core drilling and the ice-core properties

After installing the drilling system in a drilling tent from May 10–12, we started the ice-coring in May 13 and ended in May 30. We drilled the ice core mainly in daytime from 9:00 to 18:00.

The drilling system we used were the electro-mechanical ice-coring drill developed by Takahashi (1996) (Fig. 6). Unfortunately, we could not hit the bedrock due to the shortage of the winch cable. There was no clear indication in the bottom-ice-cores implying whether the depth is close to the bedrock or not.

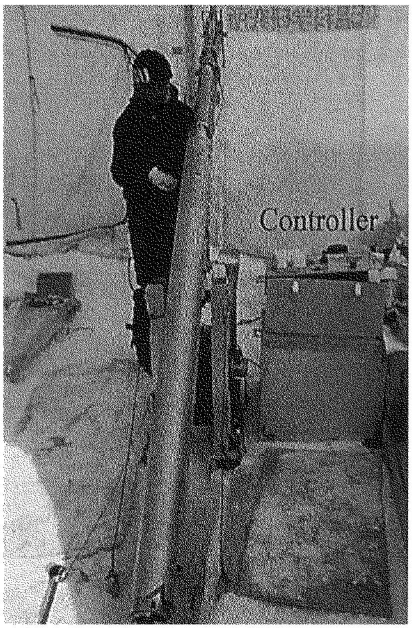

Fig. 6. Photograph of the drilling system we used for the drilling.

Figure 7 shows cumulative drilling time (h) versus depth (m) at King Col. It took 195 hours in total to drill ice cores down to 220.52 m. Average drilling speed was 1.6 m per hour for the upper 140 m where we had a trouble with the drilling. After three days of trouble-shooting, we continued the drilling. The drilling speed became as slow as 0.9 m per hour below 150 m till the end. The relatively slow drilling speed was mainly due to the hardness of the ice which was nearly −18 ℃ through the borehole.

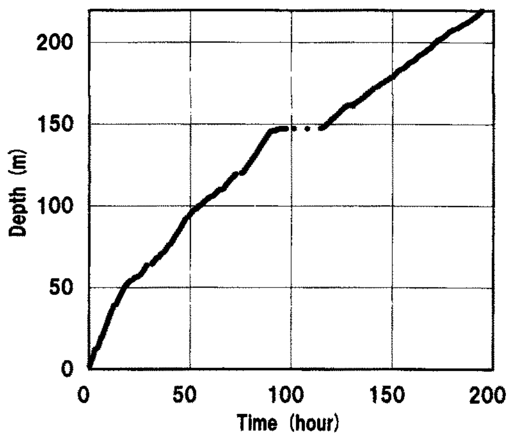

Fig. 7. Cumulative drilling time (h) versus depth (m) at King Col.

Ice core of 94 mm in diameter and 70 cm in length is constantly recovered in each drilling run. Thanks to the slower drilling speed, we could recover a good quality of ice cores until the depth of 200 m (Fig. 8). This is unusual for the ice core drilling at mountain-glaciers or small ice caps where a brittle ice usually appears below the depth of 100 to 150 m (Takahashi, 1996; Koci, 2002). We can not specify the reason why we have such a brittle ice only below 200 m. The brittle ice below 200 m may indicate that the bedrock was not far from the depth of 220.52 m.

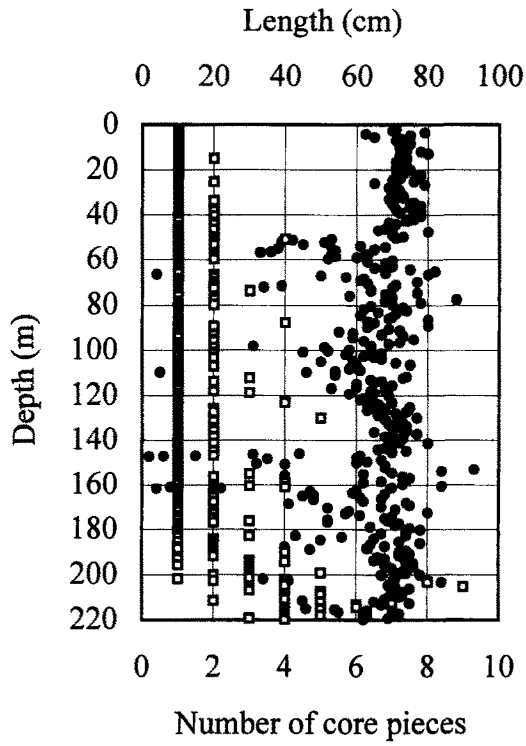

Fig. 8. Profiles of the length of each core (cm: black circles) and the pieces of the ice core obtained for each drilling run (open square).

The drilled ice cores were subjected to visual observation of stratigraphy in a snow cave just after the recovering. Stratigraphic features like grain size and bubble size/shape as well as sequences of layers were carefully checked with a luminescence light. Bulk density measurements were also made for preliminary assessment of the average density of the glacier for the calculation of radio-waves (Fig. 9). The density profile shows that the densification at this site is purely controlled by dry snow densification and melting-freezing process is insignificant at this altitude of the glacier. The pore close off depth was found at approximately 50–60 m deep.

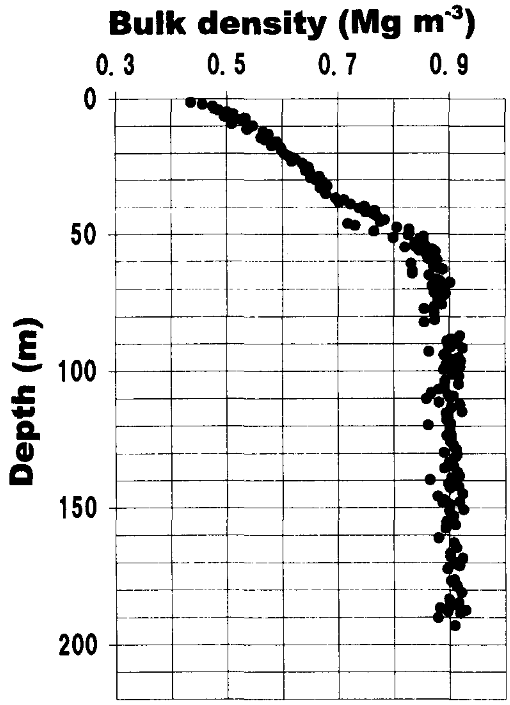

Fig. 9. Bulk density profile from the surface to the bottom of the borehole.

5. Borehole thermometry and strain grid survey

Temperature of the borehole wall was measured after the ice-core drilling from May 31 to June 1. The wall temperature was measured by a thermistor sensor (model BYE-64, Techno-seven Co. Ltd.) which was placed in direct contact with the wall of the borehole by leaf springs (Kameda *et al.*, 1993). The resistance of the sensor (12 k ohm at 0 °C) with the drilling cable (18 ohm at 0 °C) was measured by a digital multimeter with a resolution of 10 ohm. Due to the large difference in the resistances between the sensor and the cable, the cable resistance was found to be negligible. The final accuracy of the measurement in this case was ±0.1 °C.

The sensor was inserted in the borehole and stopped for measurement at every 20 m from the surface to the bottom of the borehole. The wall temperatures were measured after the system was stopped at certain depths. Readings of the digital multimeter were made at 0, 1, 5, 10, 30, 60 and 120 minutes after the installation. Figure 10 shows examples of temperature variations with time at six depths. In each case, temperatures decreased with time because the friction heat generated by the movement was dissipated to reach the so-called equilibrium temperatures. Although such a equilibrium state can never be attained in 2 hours, the 2-hours temperature seems to be nearly equal to the equilibrium temperature within a range of accuracy of measurement (± 0.1°C).

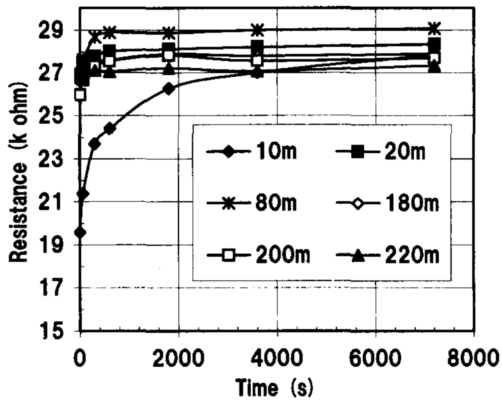

Fig. 10. Examples of the resistance (temperature) variations with time at six depths.

Figure 11 shows the profile of the 2 hours-temperatures along the borehole. Variation of the temperature is surprisingly small from −18.0 °C at 10. 00 m to −17.7 °C at 220. 52 m depths. In a top of accumulation area, temperature profile generally takes the form of coldest temperature at the surface and the warmest at the bottom. This is not the case at King Col: the upper 100 m has a reverse gradient. This may be explained either one of the followings (or the both): 1) recent increase in air temperature and/or 2) advection of cold ice from upper part of the glacier. The second possibility can not be rejected because the icefall to the north can transport ice to the King Col. This question can be answered if we could obtain data on flow field of the glacier.

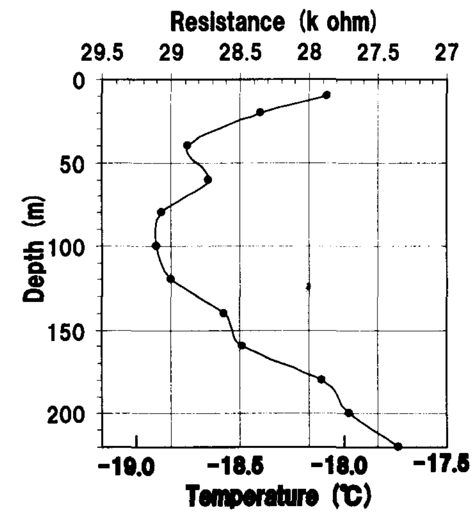

Fig. 11. Temperature profile of the wall of the borehole.

As a final field activity, we installed strain-grid points in June 1. Survey poles of 3 m were installed at 5 points: borehole, Kingcol 1, 2, 3 and 4 (Fig. 3). Each of the poles were located relative to the borehole with a pair of GPS receivers (TOPCON model GP-SX1) by rapid static method. By re-surveying the strain-grid points in the year of 2003, we expect to reveal the flow field at King Col.

6. Depth-age relationship

The 220.52-m ice core was transported to Japan within 2 months and stored in the cold laboratory of temperature at −20 °C at the Institute of Low Temperature Science. Prior to the cutting for various chemical, physical and biological analyses, we needed to know the preliminary relationship between the depth and age of the ice core. This is only available, at the moment, if we apply a simple model for age-determination. We applied "*Nye time scale*" (Nye, 1963) because it requires two parameters only, *i.e.*, ice equivalent thickness of the glacier h (m) and annual ice accumulation rate c (m a^{-1}) when the following assumptions are fulfilled: constant vertical thinning and frozen bed. The temperature profile of the glacier (Fig. 11) and the sounded depth of the glacier (≒222 m) clearly indicate that the bottom of the glacier is most probably frozen to bedrock. The first assumption is debatable, however. We can not exclude the influence of the flow from the icefall on the ice beneath the King Col. If the icefall transports a significant amount of ice to the central part of the King Col, the first assumption may collapse.

An average annual ice accumulation rate has never been obtained at this site. We attempted to estimate this parameter from the relationship between annual accumulation rate and vertical profile of firn density. Herron and Langway (1980) proposed an empirical equation showing the relationship between annual accumulation rate A (m a^{-1}) and density profile as expressed by constant C';

$$A=\left(\frac{\rho_i k_l}{C'}\right)^2,$$

where ρ_i is the density of pure ice (0.917 Mg m^{-3}), k_l the Arrhenius-type rate constant dependent only on temperature and takes the value of 0.0249 for the temperature of −18 °C. Constant C' can be obtained from depth gradient of ln $[\rho(\rho_i-\rho)]$ in Fig. 9 for the density range between 0.55 and 0.80 Mg m^{-3} and takes the value of 0.0378. Annual accumulation rate A is therefore calculated as 0.36 m a^{-1} in water. For the *Nye time scale*, we converted the sounded depth of the glacier ($d=222$ m in firn and ice mixture) and the calculated annual accumulation rate A (0.36 m a^{-1} in water) into ice-equivalent values as 200 (h: m) and 0.40 (c: m a^{-1}), respectively. The time t at depth z is now given by;

$$t=\frac{h}{c}\ln\left(\frac{z}{h}\right).$$

Figure 12 shows the depth-age relationships as calculated by the equation. Because the annual ice accumulation rate of 0.40 m a^{-1} is considered to be small with respect to the snow pits observations conducted by one of the authors (Goto-Azuma) for the years of 2000 and 2001, we tentatively calculated the relationships by using two more different ice accumulation rates of 0.50 and 1.00 m a^{-1}. In the case of $c=$ 0.40, the bottom age is nearly 1300 years and the case of $c=1.00$, it is about 500 years.

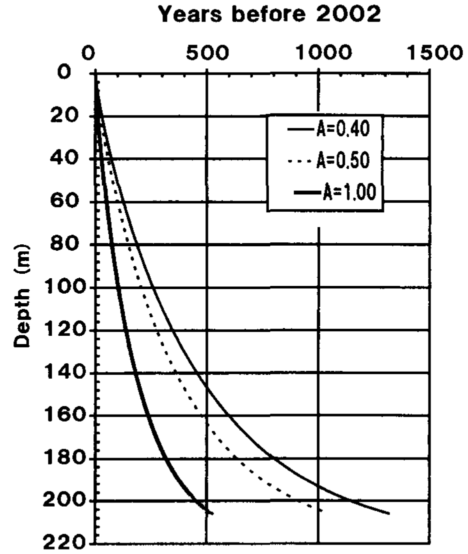

Fig. 12. Depth-age relationships estimated by *Nye time scale* with three different ice accumulation rates (0.4, 0.5 and 1.0 m a^{-1}).

7. Concluding remarks

An ice core was drilled at King Col, a saddle near Mount Logan (5959 m), in order to better understand 1) anthropogenic impact on the Pacific sector of the Arctic, 2) decadal and interdecadal climate changes in the North Pacific, and 3) dynamical behavior of cold mountain glaciers. Firstly, we conducted a radio-echo sounding with an impulse ice-penetrating radar at five sites and detailed topographical survey to determine the drilling site. An ice core drilling down to 220.52 m-deep, temperature measurements along the borehole, and installation of a strain-grid network at the King Col, were conducted subsequently. The thickness of the glacier was estimated as 190 to 270 m at the center of the King Col, while the surface is nearly flat with minor ridges extending from north to south. The ice core was good in quality and showed that the drilling site was categorized in dry snow zone. The glacier is nearly isothermal from −18.0 °C at 10 m-depth to −17.7 °C at the bottom of the borehole. The *Nye time scale* indicates that the age of the ice core varies from approx. 500 to 1300 years with varying ice accumulation rates from 1.0 to 0.4 m a^{-1}.

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