GLACIOLOGICAL RECONNAISSANCE OF AN ICE CORE DRILLING SITE, PENNY ICE CAP, BAFFIN ISLAND

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ABSTRACT. A site situated close to the main divide of the Penny Ice Cap, Baffin Island was occupied in 1979 for the purpose of determining the suitability of this ice cap for providing proxy climatic data and other environmental time series for a span of 1000 A. A 28 m core was extracted and analysed for stable oxygen isotopes, tritium concentration, pH, electrolyte conductivity, major ion concentrations, and particulate concentration.

An adjacent dedicated shallow core was analysed for pollen content to determine if a significant seasonal variation in the pollen rain existed. From these observations, and data from other studies made on the stratigraphic character of the core, the mean net accumulation rate over the approxi- mately 30 year period covered by the core is found to be about 0.43 m water equivalent per year. This is in agreement with a single value determined 25 years earlier for a nearby site (Ward and Baird, 1954). The mean annual temperature in the bore hole was found to be close to -14.4°C, possibly some 2-5 deg warmer than the expected mean annual surface air temperature at the site. This difference is due to the expulsion of latent heat upon freezing of melt water at depth in the snow-pack which gives rise to the many ice layers observed in the core. The percentage thickness of ice layers per year may be correlated with summer temperatures.

Total ice depths were measured using a 680 MHz radar echosounder. In the vicinity of the divide, over an area of 1 km², the ice depths vary from about 460 to 515 m. These values compare favourably with values determined from a prone traverse with a 32 kHz echosounder. An adjacent site, a 1 km² area of Penny ice Cap, south-east Baffin Island (Fig. 1) was carried out in 1953 by the National Antarctic Institute of North America expedition (Baird and others, 1953; Ward and Hargrave, 1954) and by Weber and Andrieux (1970). The former publication reports on measurements confined to the far south-eastern sector of the ice cap, about 25 km distant from and possibly lower than the site here described. The latter publication gives ice depth data to within 11 km to the north-west of the present site.

Four low domes, each reaching to about 1900 m above sea-level, exist in the east-central part of the ice cap (Fig. 2). The site, occupied in April-May 1979, lies between the two most northerly domes, but nearer the southern one of the two. The intention was to occupy this latter dome, but in landing by aircraft, the surface relief was lacking in contrast and a misidentification of position was made. Because of limited surface mobility, it was decided to establish the reconnaissance camp at the landing site about 500 m to the east of the main ice-cap divide).

The present site reconnaissance was carried out to determine if useful paleo-environmental information might be extracted from the ice cap and where a suitable deep drill site might exist. Of prime interest was the potential of the core for yielding proxy climatic and other atmospheric data, and, if positive, what useful time span was likely to be covered. Such data would be useful input to previous climatological modelling studies for Baffin Island (Barry and Fagaras, 1968; Andrews and Barry, 1972; Andrews and others, 1980), as well as to Holocene climatic fluctuations and palynological studies over the same interval (Miller, 1973).

Climatic data from this area, in conjunction with similar data from other parts of the high Arctic (Barry and others, 1975) would be extremely useful in long-term studies related to the behaviour of the Icelandic
From available field evidence (Dyke and others, 1982) it may be assumed that the present location of the Penny Ice Cap divide is not significantly different from its location at any time over the last 100 years. From knowledge of the position of the ice margin during most of that time, it is unlikely that the ice thickness near the divide has changed by more than a few per cent over that time. This allows a relatively straightforward interpretation of an ice core that might be retrieved by drilling through the divide.

**SITE SURVEY**

A site, about 500 m east of the divide of the ice cap, at lat. 67°14′N, long. 65°43′W, altitude 759 m (Fig. 2) was occupied from 24 April to 14 May 1979. During this time, a continuous 20 m firn and ice core was recovered for oxygen-isotope and other analyses, a 6 m core was obtained for pollen studies, an accumulation pole array was established, and some ice depth soundings were carried out. Ice temperatures were monitored in the 20 m bore hole. During this time, some limited meteorological measurements were also recorded.

The camp was used as a reference point for an airborne radar ice thickness survey of the complete ice cap, carried out on 9 May. Results of this survey will be published separately.

**Site characteristics**

The site is located in the percolation zone (Paterson, 1981) and most years, except the very coldest, are characterized by moderate to high ice-layer formation. Spring and winter snow is quite heavily covered by sastrugi formed by the intense storms which occur on the ice cap.

Core retrieval and processing

Core drilling was accomplished with a standard SIPRE corer. The core was immediately placed into plastic tubing and stored in a transit case set in a snow pit covered by an igloo. The core was later air freighted to Ottawa. Apart from a short section below the base of the pit, which was poorly packaged and labelled, the core is considered good and will be referred to in the text as complete. A separate 6 m core was retrieved for pollen analysis, which has now been completed (a paper on this is in preparation by S. Short and G. Holdsworth). This study showed that significant seasonal variations in pollen rain do exist at this site but that in order to obtain a satisfactory spectrum showing clear summer-winter oscillations (i) a larger horizontal cross-sectional sample area is required and (ii) cutting of samples should be along summer-winter boundaries. This latter requirement can only be achieved after other analyses of the core have been carried out.

The pollen data could be used as an independent check on stratigraphic interpretation. More important, however, is the potential of pollen variation data (in conjunction with oxygen isotope data) for throwing light on air-mass circulation patterns.

Some core processing was carried out in the science laboratory in Frobisher Bay, the remainder was done in the Environment Canada cold rooms in Ottawa.

**CORE ANALYSES**

All core handling was carried out with double plastic gloves and a face mask. Samples were cut with a cleaned stainless-steel saw and then placed in "whirl-pak" plastic bags for melting.

Core stratigraphic interpretation was carried out simultaneously with sample preparation. The densities of the firn, iced firn, or ice layers were determined.
Some limited chemical analyses were carried out. Figure 9 shows the complete Na+ concentration profile. The analyses were done at the Environment Canada Laboratories (ECL), Ottawa. Despite the fact that no ultra-clean procedures could be adhered to, the values for most of the core are at the same general level as those given by Busenberg and Langway (1979) for some Greenland sites, and are therefore thought to be free of gross contamination.

In order to examine the interval 10-12 m in more detail, remaining core was cut at 10 cm intervals and resubmitted to ECL for analysis for Na+, K+, Ca²⁺ and Mg²⁺ (Fig. 10). The levels of Na⁺ are consistent with those of Figure 9.

As a final check, principal cation analyses were performed on the samples submitted to the PCSP laboratory. The results (Fig. 11) show much greater variation in adjacent values than do the corresponding data in Figure 10. This is because the sampling interval for the PCSP samples was much less than the previous arbitrary 10 cm sampling interval. Generally, the higher ionic concentrations in Figure 11 apply to the solid ice samples. This is an expected result, since salts would tend to be leached out of snow and concentrated in the refrozen melt water. There are, however, significant differences between the means of the corresponding data sets, and the reasons for this are assumed to be related to sample preparation and measurement. Compared with Figure 11, the data set in Figure 10 has lower means over the interval 10-12 m. These are for Na⁺, 0.08; K⁺, 0.013; Ca²⁺, 0.053; and Mg²⁺, 0.024 (p.p.m.).

Analyses for oxygen isotopes were carried out on 200 samples cut at 10 cm intervals along the complete core. The measurements were done at the Geophysical Isotope Laboratory, Copenhagen, and are shown in Figure 4.

Tritium concentration measurements were made on the water remaining from the oxygen isotope sampling. These measurements were carried out at the Radiation Protection Bureau, Ottawa. The results are shown in Figure 5.

Analysis of the complete core for conductivity and pH was carried out with special attention being paid to the depth interval 9.5 m to 12.5 m which contains a large electrolytic conductivity disturbance (Fig. 6) thought initially, but erroneously, to be caused by the Mt. Agung volcanic eruption of March 1963. The pH measurements presented in Figure 7 represent two independent sets of data obtained from separately cut sequences and using different pH meters. The major trends in both pH and electrolytic conductivity are all reproducible.

Conductivity and particulate analyses were carried out on a quarter section of the core, at the laboratories of the Polar Continental Shelf Project (PCSP), Ottawa. Sample intervals were irregular as a result of separating firn from ice. Most sample lengths were close to 5 cm. Figure 8 shows that this procedure resulted in a much higher variation in concentration values compared with the values shown in Figure 6.

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DISCUSSION OF CORE ANALYSES

Isotope data

The $\delta^{18}$O plot (Fig. 4) shows that seasonal $\delta$ variations are locked in, and that the core, when interpreted with the help of other data, covers a period of about 30 years. This time scale has been calibrated absolutely at several points, using the tritium concentration diagram (Fig. 5). This shows calibrating peaks in 1956, 1958, 1959, 1962, 1963 (corresponding to pre-moratorium atmospheric nuclear warhead tests), 1964, 1965, 1966, 1968, and 1969. Although it has only been demonstrated at a few points, it is assumed that the isotope seasons are everywhere in phase with climatic seasons. Prior to 1956, there may be an error of $\pm 1$ year in the time scale.

General stratigraphy

The base of the core is seen to be penetrating snow deposited in about 1969. The interesting result is that a splice may now be made with an 18.5 m core extracted 26 years previously, from a site of similar altitude, 25 km to the south-east (Location A-1, Fig. 2). The core stratigraphy from Ward and Baird (1954) is shown re-drawn in Figure 3(b). Their value for the 1952-53 net accumulation (0.43 m water-equivalent) is exactly the same as the 1949-79 average deduced from the present work.

The well-known cold years of 1972 and 1973, as well as the cool period 1949-53 are correctly reflected in the $\delta$ data (Fig. 4) and are confirmed by the stratigraphy (cooler periods are marked by less ice). Figure 3(b) shows that the first 6 m of the core is almost devoid of ice, indicating cool summers. Although Ward and Baird (1954) do not provide a chronology, it is probable that this period extends from 1945-53 (giving a mean net accumulation rate of about 0.40 m a$^{-1}$). The onset of heavy ice layering below 6.3 m would then logically correspond to the warmest period (1935-45) observed so far this century for most North American localities (Budyko, 1974; Mitchell, 1961).

The cavities which occurred in the 1953 core are interesting, being evidently due to vertical creep of snow bridges spanning a crevasse. During warmer summers, the presence of melt water would accelerate the deformation of the bridges. Subsequent winter snow would form cornices over the old iced bridges and a cavity would result. The A-1 core, allowing for the cavities, has a reduced length of 18.5 m and probably extends back to about 1922, which is near the beginning of the general warming period this century (Budyko, 1974). It is possible that in periods much warmer than the last 30 years, the $\delta^{18}$O record may not be so clear in...
exhibiting significant seasonal variations. This would not, however, present an insurmountable problem in core interpretation. In a climatology section below, the correlation between the amount of ice in the core and the mean monthly maximum (July/August) temperatures will be discussed.
Electrolytic conductivity and pH measurements

The tritium results give an unambiguous 1963 date on ice just above the conductivity disturbance (see Fig. 6) at about 11 m depth. Any fallout from the large Mt. Agung event would be expected to arrive in 1964. (There is a minor but significant conductivity peak at 9.5 m depth which corresponds to mid-1964.)

A possible source of the major disturbance in both the conductivity and the pH profiles, peaking in 1961 and 1962 and continuing through 1963, is northern-hemisphere volcanism, which, according to recent records (Simkin and others, 1981), began a new active phase in the Pacific North-West in the early 1960's compared with generally low activity in the latter part of the previous decade. A similar pattern in conductivity and pH was found in a core from the Yukon Territory (G. Holdsworth, unpublished data) and these core data are correlated primarily with volcanic eruptions in continental Alaska, the Alaska Peninsula, the Aleutian Islands, Kamchatka Peninsula, and the Kurile Islands. In particular, Mt Trident (lat. 58°14'N; long. 155°07'W.), which began a new series of major sulphurous emissions in 1961 (written communication from J. Kienle; Simkin and others, 1981), began a new active phase in the Pacific North-West in the early 1960's.

The common ion chemistry may be used to further interpret the core. From the base of the core to a depth of 2 m, the background Na⁺ concentration (Fig. 9) is close to about 0.02 p.p.m. with a significant departure from this level in the interval from about 12 m to about 6 m. The highest concentrations are to be found between 12 m (1960) and 9.5 m (1964), the interval that broadly coincides with the anomalies in conductivity, pH, and particulates. Moreover, certain Na⁺ peaks in 1964 (9.8 m), 1976 (2.2 m), and 1977 (1.2 m) also occur at the same time as those in a Na⁺ concentration profile for a core spanning 20 years obtained from the Aigassiz Ice Field, Ellesmere Island (R.M. Koerner, unpublished data). This would seem to indicate, at least for some of the Na⁺ fallout, that the two sites were receiving aerosols from the same source.

The consistently higher Na⁺ levels in the upper 1.5 m could be due to contamination of the snow-pit samples, and therefore interpretation in this interval is avoided.

Annual layer identification

Seasonal or annual peaks in cation (and anion) concentrations have been recognized in firm cores (Langway and others, 1977; Busenberg and Langway, 1979) and can be used to determine the thickness of annual layers along the core. The established depth-time scale (Fig. 4) has been used to determine if seasonal (annual) variations in ionic species exist. The time annotations on Figures 8, 9, 10, and 11 show to what extent these variations can be recognized. The data obtained from the shorter sample length (approximately 5 cm) is clearly superior to those obtained from the samples with an arbitrary length of 10 cm. This indicates that for this work, at least eight samples per annual layer should be cut (Langway and others, 1977). Conductivity peaks and, to a less convincing degree, particulate concentration peaks occur approximately at the centre of an annual layer from 1960 to 1964 (Fig. 8).

Figures 9 and 10 show only weak annual signatures, with the more convincing signals being found in the K⁺ concentrations. Figure 11 shows that some annual signatures exist in the Na⁺, Ca²⁺, Al³⁺, and Si⁴⁺ data. The latter, however, exhibit the best signatures with almost unambiguous peaks (or double peaks) occurring from 1959 to 1964. The existence of the annual double peaks in both the particulate and the Si⁴⁺ concentration profiles is mutually consistent and may be useful in identifying annual layers in deeper core.

Proxy climate information derived from the core

A functional relationship is assumed to exist between δ¹⁸O values and the corresponding air temperature at the time of precipitation (Dansgaard and others, 1973). This relationship might be extended to apply to annual means of individual values of δ and temperature. The data and time scale in Figure 4 may
be used to compute \( \delta \), the mean annual values of \( \delta \), if the precipitation pattern were roughly the same in each year (but not necessarily evenly distributed within a year) then this \( \delta \) time series might be expected to show some correlation with a mean (annual) temperature time series for the site, or in the absence of such data, with a corresponding temperature time series for the nearest climatological station. Because the \( \delta \) values thus derived (Fig. 12a) are naturally weighted in terms of the schedule of precipitation on the ice cap, it may appear unrealistic to attempt a direct correlation with mean annual air temperatures at instrumental stations along the coast (Fig. 1). Therefore, the mean annual temperatures for Broughton Island and Cape Dyer were recomputed by weighting mean monthly temperatures according to the monthly precipitation. This series yielded weaker cross-correlations with the ice cap \( \delta \) time series than the unweighted temperature time series. It could be concluded that the annual precipitation schedule on the ice cap is significantly different from the precipitation schedule at the nearest coastal stations. For this reason, no weighting has been applied to any of the time series.

Figure 13a and c shows the mean annual temperatures from 1960-79 for Cape Dyer and from 1969-79 for Broughton Island, respectively. Total annual precipitation for each station (Fig. 13b,d) is also shown to indicate the great local variability in magnitude and time. Figure 13e shows the much longer time series for mean annual temperature for Frobisher Bay, 300 km south-west of Pangnirtung (Fig. 1). Cross-correlation coefficients between the \( \delta \) time series and the time series of mean annual temperature (Fig. 13a,c,e) are given in Table I. Cross-correlation coefficients between instrumental stations are seen to be high whereas the coefficients corresponding to the \( \delta \) series are low, even when using five-year running mean values. However, the fact that the coldest year (1972) in the last two decades and the cool period 1949-53 can be seen in the \( \delta \) profile, suggests that extremes and longer-term trends might be seen in a longer time series.

Dansgaard and others (1973) give data on \( \delta \) versus altitude for west mid-Greenland firn that indicate the Penny Ice Cap snow (which has a three decadal mean of \(-24.6^{0}/00\)) is slightly less depleted in \( H_{2}^{18}O \) than at the corresponding altitude (c. 2000 m) in Greenland. The site in Greenland most comparable to the summit of Penny Ice Cap is Dye 2 which is slightly over 2000 m in altitude and has a mean annual temperature of \(-16.7^{0}/C\) (Herron and Langway, 1980).

A mean annual air temperature for the Penny

TABLE I

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<tr>
<th>CROSS-CORRELATION COEFFICIENTS BETWEEN TIME SERIES</th>
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<td><strong>Frobisher Bay (MAT)</strong></td>
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<td>Ice cap ( \delta^{18}O )</td>
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<td>Frobisher Ray (MAT)</td>
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<td>Frobisher Bay MMODT %</td>
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<td>Frobisher Bay MMODT</td>
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\( \delta^{18}O \) = percentage ice in core per annual layer

* MAT = Mean annual temperature; \( \# \) MMODT = Mean maximum daily (July) temperature

Cross-correlation coefficients: \( R(L) \pm 2 \) standard deviations.

\( L \) = Length (years) of moving averages. All cases are for zero lag.

Underlined values are significantly different from zero at two standard deviations.
Fig. 13. (a) Mean annual temperature (°C) and (b) total precipitation (mm water per year) at Cape Dyer; (c) mean annual temperature and (d) total annual precipitation at Broughton Island. (e) Mean annual temperatures for Frobisher Bay (1947-79) and Pulloping Island (1948-68).

Ice Cap site might be estimated from the mean annual air temperature at Cape Dyer (-10.4°C) (Fig. 13a) and an estimate of the mean annual adiabatic lapse rate. Orvig (1954) gives a value of about 0.0056 deg m⁻¹ for the May-August period between 400 m and 2000 m a.s.l. Winter radiosonde data for Frobisher Bay and Arctic Bay (Orvig in Rand Corporation, 1963) indicate the existence of strong inversions, so the mean annual lapse rate could be considerably less than and possibly half this value. Taking the upper limit, a mean annual air temperature at 1938 m could be as cold as -19.5°C or, in the lower limit, colder than -15°C.

The temperature-depth profile in the bore hole (Fig. 14) shows the mean annual ice temperature to be close to -14.4°C. Because melt water refreezes in situ, latent heat generated is partly retained by the snow-pack thus raising its temperature. A calculation given in Appendix A indicates that this heating of the snow-pack might be by several degrees. Hieber and Andrieux (1970) report a mean annual (firn) temperature of about -13°C at 1938 m altitude. This value seems compatible with the present data.

If it is assumed that the slope of the graph of $\theta$ versus mean annual temperature ($T$) is close to that observed for cold dry snow (approximately 1.0°/00 deg⁻¹) (Dansgaard and others, 1973), then the equation for the Penny Ice Cap would be

$$\theta = \frac{T}{b} - b$$

where $b$ has a value between 5 and 8°/00. It is still assumed that $\theta$ is the unweighted value.

Figure 12b shows the water-equivalent of the net annual increments in the core. A two-year smoothing has been applied to the data (dashed line) since a possible ± 1-year error exists in parts of the time scale. There would then be no reason to apply lags to the series before attempting to cross-correlate with other time series. It turns out that correlations between any of the precipitation time series (Figs 12b, 13 b and d) are hardly significant, although it is
possible, visually, to connect some extreme events. This result is not unexpected since the series in Figure 12b represents wet accumulation and that in Figure 13 total accumulation, and because of the failure to improve temperature cross-correlations using precipitation-weighted temperature data.

The net accumulation values 1969-74 have no correlation with specific net mass balance data given for nearby 'nas' Glacier (Weaver, 1975) for the same period. This indicates that mass-balance data taken from different glaciers and from different elevations in this area cannot be compared over these time spans.

Figure 12c shows the percentage (cm) of ice in each annual increment of the core. A relationship might be expected to exist between 3 and the number of days during the summer when daily temperatures were at or above a value sufficient to cause surface melting. The parameter closest to conveying this information is the Mean Maximum Daily Temperature (MMDT) (computed for each month and published in station climatological summaries). In this case the MMDT value is usually a maximum in July. Sometimes the August value is greater, in which case this value is taken. Figure 15 shows available time series of MMDT for Frobisher Bay, Cape Dyer, and Broughton Island, which have the best correlations with 3 when data are smoothed by 3-5 year moving averages (Table I).

By analysing Baffin Island station records for the period 1960-69, Bradley and Hillier (1972) found that generally, the "ablation" period (June-August) was becoming cooler, whereas the "accumulation" period (September-May) was becoming warmer by about the same amount (2 deg). The data in Figure 12c seem to show a response to this in that, if averaging is made over two-year intervals, there is an indication of decreasing ice in the firm over this period. The correlations between 3 and station MMDT values are significantly higher than correlations between 3 and MAT values (Table I). These latter correlations might be improved by a weighting procedure applied to the 8's based on knowing the precipitation regime on the ice cap.

**ICE THICKNESS MEASUREMENTS**

Ice-cap thickness profiles were determined independently by surface and airborne operations in May 1979.

**Temperature Profile in the Bore Hole and the Ice Cap**

The temperature-depth profile (Fig. 14) shows temperature values measured by thermistors in early May, 1979. The 10-12 m firm temperature (-14.4°C) is expected to be several degrees warmer than the mean annual air temperature at the site (Appendix A).

Assuming that the present 12 m thickness is approximately representative of the long-term value, that the average accumulation rate was approximately constant over the same period, that the divide has essentially been stationary, and that the ice thickness has been roughly constant over 10^2-10^4 years, it is possible to estimate the basal temperature of the ice cap using a steady-state solution for an ice divide (Appendix B). The result is that the basal ice temperature is well below freezing (-9 to -10°C).
and for the height of the antenna above the snow, and assuming an average electromagnetic wave speed of $168.5 \text{ m s}^{-1}$ (Weber and Andrieux, 1970; Jones, 1972), total ice thicknesses are found to lie between 457 and $516 \pm 10 \text{ m}$. Figure 16a shows the ice thickness map with two profiles given in Figure 16c. Ice thickness is increasing towards the nearest dome to the southeast, a result that is confirmed by the results of the airborne survey.

**Airborne survey**

On 9 May a radar overflight was carried out. A C-130 aircraft, operated by the U.S. Navy VX6 squadron in conjunction with the U.S. National Science Foundation and the Technical University of Denmark made a series of passes over the entire ice cap during a 7.5 h period. An inertial navigation system was used and the camp served as a navigation check point. Two transmitting frequencies (60 and 300 MHz) were used simultaneously at a pulse width of 250 ns (giving a range resolution of 20 m). Data have been supplied by Overgaard (unpublished) although only a small percentage of the total data are reproduced here. Figure 17 shows two cross-sections produced from the photographic record of the continuous Z-scope traces for the divide area near the core site. Ice depths are seen to be in good agreement with the values determined using the surface equipment. Of particular significance are the existence of internal reflections seen at both frequencies. The reflecting horizons are not continuous nor of equal strength.

Near the divide, a reflection was detected at a depth of about 270 m (Figs 16 b, c and 17). This corresponds to a date of $940 \pm 50 \text{ A.D.}$ and may be a major volcanic or climatic time horizon. Gudmandsen (1975) has described similar reflecting layers for the Greenland Ice Sheet.

**A TIME-DEPTH SCALE FOR THE ICE CAP**

A number of assumptions must be made in order to estimate the age of the ice at a given depth. First, the surface is similar to Dye 2 (Herron and Langway, 1980), the firn-ice transition is assumed to be at $50 \pm 5 \text{ m}$. Secondly, the vertical component of velocity at the surface is assumed to be constant and equivalent to the long-term accumulation rate. Thirdly, a steady-state ice thickness is assumed.

As an approximation, the observed form of the variation $v(a)$ of velocity with depth for Devon Ice Cap (Paterson, 1981, p. 70) has been used with the specific constraint that at depth $a = 20 \text{ m}$, $v = 30 \text{ a}$. Equivalent empirical expressions for $v(a)$ for Penny Ice Cap are:

$$v(z) = 0.187 \ln(1 + z) + 1.2 \quad 0 \leq z \leq 50 \text{ m}, \quad (1)$$

$$v(z) = V_1 (1 - z/H_1)^m \quad 50 \leq z \leq 480 \text{ m}. \quad (2)$$

Where $V_1$ is the ice equivalent vertical velocity at the ice equivalent surface of the ice cap, $a_1 = a - a_0$, which is the vertical distance measured from the present surface to the ice equivalent surface, $H_1$ is the ice equivalent thickness of the ice cap, $(H_1 = H - a_0)$, and $m$ has a value of about 1.3. The age at a given depth $a$ is obtained from

$$t = \int_0^a \frac{1}{v(z)^{-1}} \text{d}z. \quad (3)$$

The upper curve (1) meets the lower curve (2) at about $50 \text{ m}$ (the firn-ice transition) where by integration of
Fig. 18. Predicted depth-age relationship for the divide mno for a pre-Holocene thickness of 480 m. Curve 1 corresponds to a uniform vertical velocity at the surface of 0.47 m a⁻¹; curve 2 to a vertical velocity of 0.4 m a⁻¹. The reflecting horizon at 270 m depth corresponds to an age of 1530 years on curve 2. Point H (3) marks the Holocene-Pleistocene boundary, for curve 1 at 5 m above the bed, and for curve 2 at 8 m above the bed.

(1) according to Equation (3) the age of a layer (z = 50) is about 88 years (± 10 a). Taking zₙ = 16 m, and ignoring further densification, the age of the ice in the depth interval 50 m < z < 480 m (34 m < z < 464 m) is:

\[ t(z = 50) = t(z_{n} = 16) + \int_{z_{n}}^{z} v_{s}(1 - z/480)^{-0.6} \, dz, \]  

(4)

Figure 18 shows the predicted depth-time curves for m = 1.3 and for two values of vₛ t. The first is equivalent to the present surface net balance and the second is about 14% less. The selected value of m is equivalent to the present surface net balance and the acid-volcanic reflecting horizon at Camp Century, Greenland, originally identified by Robin and others (1969). There, Paterson (1976) found that a surface velocity of 0.4 m a⁻¹, for vₛ t = 0.40 m a⁻¹, produces the best fit to the depth-time scale for Devon Ice Cap. Paterson (1976) found that a surface velocity of 0.4 m a⁻¹, for vₛ t = 0.40 m a⁻¹, produces the best fit to the depth-time scale for Devon Ice Cap. Paterson (1976) found that a surface velocity of 0.4 m a⁻¹, for vₛ t = 0.40 m a⁻¹, produces the best fit to the depth-time scale for Devon Ice Cap. Paterson (1976) found that a surface velocity of 0.4 m a⁻¹, for vₛ t = 0.40 m a⁻¹, produces the best fit to the depth-time scale for Devon Ice Cap. Paterson (1976) found that a surface velocity of 0.4 m a⁻¹, for vₛ t = 0.40 m a⁻¹, produces the best fit to the depth-time scale for Devon Ice Cap.

The relationship between oxygen isotope ratio and air temperature is not simple, although certain features characteristic of the last few decades of the Arctic climate may be recognized. In order to clarify this relationship a considerable amount of data processing would seem to be necessary.

CONCLUSIONS

On the Penny Ice Cap divide a suitable site exists for retrieving a core which would cover the complete Holocene time period. The ice below about 450 ± 5 m depth will have annual layers compressed to under 1 cm thickness. Pleistocene ice should be encountered at from 5 to 8 m above the bed, oxygen isotope variations due to seasonal temperature changes appear to be locked into the ice, and by diffusion these oscillations will probably be erased in several thousand years (Johnsens, 1977).

The climate data to emerge from the core will require careful treatment. It is evident that the percentage ice (x) per annual layer has a significant correlation with summer temperatures as Koerner (1977[a]) found for Devon Ice Cap. This information however is dependent on successfully identifying summer melt layers in the core, a task which becomes increasingly more difficult with depth. The relationship between oxygen isotope ratio and air temperature is not simple, although certain features characteristic of the last few decades of the Arctic climate may be recognized.

ACKNOWLEDGEMENTS

I wish to acknowledge the efforts of Dr. John T. Andrews in stressing the need for a core-drilling program on the ice cap. The help of Robert Redhead, superintendent of Auyuittuq National Park (Pangnirtung) and the cooperation of Andrew Theriault of the N.W.T. Government (Frobisher Bay) is kindly acknowledged. I am particularly thankful to John Gunn who accompanied and helped me in the field. For arranging a radar ice depth-sounding overflight, I wish to acknowledge the help of Dr. P. Gudmandsen of the Technical University of Denmark (Copenhagen), Dr. R. Cameron, U.S. National Science Foundation, and Dr. R. Ramseier, Environment Canada. I am most grateful to Dr. S. Overgaard for providing ice thickness data.

The oxygen-isotope analyses of ice-core samples were carried out at the Geophysical Isotope Laboratory (Copenhagen) under the direction of Dr. P. Gudmandsen. I am indebted to Dr. N. Fisher for providing me with the final annotated 18O values. The tritium analyses were carried out at the Radiation Protection Bureau (Ottawa) under the direction of Dr. R. Prandtl and D. Meyerhoff.

I thank Dr. R. Koerner of the Polar Continental Shelf Project, Ottawa for performing particulate, chemical, and conductivity analyses on part of the core. Other chemical analyses were carried out by Martha Bowman and Dr. Laura Johnson (Environment Canada). I thank Dr. P. Cohen (Environment Canada) who planned and evaluated the statistical analyses made on the time series. Drs R. Koerner, J.R. Weber, D.H. Lennox, and P.D. Baird kindly read and checked the manuscript.
APPENDIX A. ESTIMATE OF THE AMOUNT OF HEATING OF THE SNOW PACK BY EXPULSION OF LATENT HEAT

In order to provide an estimate of the temperature rise in the snow (firn), and hence to find the difference between the mean annual air temperature and the mean annual firn (ice) temperature, due to freezing of melt water, a simplified model is used, in which a thin, infinite plane heat source is considered to exist at the surface of a semi-infinite solid. The equation of one-dimensional heat flow in the downward direction is taken to be:

\[ \frac{dT}{dt} = k \frac{d^2T}{dz^2} \]

(A1)

where \( T' \) is the temperature rise (or perturbation) above the ambient state without latent heat generation, \( t \) is time and \( k \) is the thermal diffusivity of the snow.

A solution of Equation (A1) for the above model is:

\[ T = \left( \frac{4\pi t}{m^2} \right)^{1/2} \frac{Q}{k} e^{-z^2/4m^2} \]

(A2)

for the case of a plane heat source \( Q \) per unit area at \( z = 0 \). The density of the snow is \( \rho \) and its heat capacity \( C \). In reality, heat is generated within the first \( m \) m snow depth. For modelling purposes heating shall be considered to take place within the thin layer at the surface, but initially with all the heat transferred downwards. This imposes an upper limit on the estimated temperature rise in the firn (and hence in the ice lower down). It was determined that 25% of the annual snow layer was converted into ice on average. If snow at density \( \rho \) is now converted to ice of density \( \rho_i \), then the total heat released in the refreezing of the water is approximately \((\rho - \rho_i) \times 0.25 \times 10^3 \times 3.4 \times 10^7 \) J kg\(^{-1}\). The heat thus released is

\[ Q = 4.5 \times 10^7 \text{ J m}^{-2} \text{ m}^{-1} \]

Equation (A2) is now evaluated at \( z = 0 \) for \( \varepsilon = 1 \), to yield \( T' = 3.9^\circ \text{C} \).

This process is an annual event, thus the mean annual firn (ice) temperature will be consistently warmer than the mean annual air temperature by about 4°C. If half the heat is lost vertically upwards then the temperature difference will only be about 2°C. The actual difference is likely to lie between these limits.

This estimate is consistent with the estimates of Hooke (1976[a]) for the Barnes Ice Cap divide.

APPENDIX B. STEADY-STATE TEMPERATURE DISTRIBUTION THROUGH AN ICE DIVIDE

A solution for the temperature distribution below a divide in a model ice sheet was given by Robin (1955). In the model, a constant vertical strain-rate was assumed throughout. Such a vertical strain-rate distribution is not consistent with a cold-based glacier and the computed basal temperatures tend to be colder than observed, where data are available. For thin ice caps, the discrepancy is not serious (0.6 deg for a thickness of 500 m) but for thicker (>1000 m depth) ice sheets the discrepancy may reach several degrees.

An expression for the vertical flow rate through the divide was obtained previously (Equation 2). Substituting this into the original heat-flow equation (e.g. Paterson, 1981, equation 16) the following equation is obtained after some simplification:

\[ \frac{dT}{dz} - \frac{(9m/k)(1 - z/\ell^2)}{m} \frac{dT}{dz} \approx 0 \]

(B1)

Where \( T \) is temperature, \( v_{95} \) is the equivalent vertical velocity of the ice surface, \( k \) is the thermal diffusivity of the ice, \( \ell \) is the equivalent ice thickness, and \( z_i \) is depth measured downwards from the surface.

Using the boundary conditions

\[ T = T_0 \text{ at } z = 0 \]

and \( d^2T/da^2 = 0 \) for the geothermal gradient at \( z = \ell \)

and putting \( a = v_{95} \ell/k \), the depth at temperature \( T_i \) is then given by:

\[ T(z) = T_0 + G \int_{0}^{z} \exp(-a(z/H))^2 dz \]

(B2)

For \( m = 1 \), this equation reduces to the Robin (1955) solution, and may be evaluated in terms of the error function. Numerical solutions of Equation (B2) recast in the incomplete gamma function form, for a range of values of \( a, \ell, \) and \( m \) for steps of 0.1 \( \ell/\ell_1 < 1.0 \) have been obtained. Using values of \( v_{95} = 0.40 \text{ m a}^{-1}, \kappa = 36 \text{ m}^2 \text{ a}^{-1}, m = 1.3, G = 0.019 \pm 0.004 \text{ deg m}^{-1}, \ell_0 = 14.4^\circ \text{C} = 1 \text{ deg} \), and \( H_1 = 464 \pm 10 \text{ m} \), the basal temperature is about \( 2^\circ \text{C} \). More sophisticated modelling is possible (Paterson and Clarke, 1978) when deeper data are obtained.

REFERENCES


Note: The document is a list of references, not a standalone text. The original publication information is included.