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Devon Island Ice Cap: Core Stratigraphy and Paleoclimate

The Canadian Arctic ice caps continue to lose mass in response to the unusual warmth of the past 100 years.

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Knowledge of polar paleoclimate has been advanced considerably in the last decade by the study of oxygen-18 variations (*1, 2*) and, to a lesser extent, variations of elemental and microparticle concentrations in ice cores from Greenland and Antarctica (*3, 4*). So far, however, not much attention has been paid to the relationship between the stratigraphy of the ice and climate. Some encouragement for such an approach was given by a study of the textural variations of the ice in a core from the Meighen Ice Cap, Northwest Territories, Canada (*5*). This study allowed conclusions to be drawn about the ice cap's dynamic history and the changing climate associated with its growth. Hibler and Langway (*6*) inferred climatic change from a statistical analysis of melt features in a core from central Greenland. To explore further the paleoclimatic variations in the Canadian Arctic, the climate-stratigraphy approach has been used in a study of a series of three cores from the top of the Devon Island ice cap (Fig. 1), at an elevation of 1800 meters above sea level, where accumulation is 220 kilograms per square meter per year in the form of firn, and melting occurs in about nine summers out of ten. Two of these cores were 20 m apart and penetrated to bedrock 299 m below the surface. The third, 300 m from the other two, was from the surface to a depth of 230 m. In addition, a series of 12-m surface cores from various locations in the Queen Elizabeth Islands are considered (Fig. 1).

Meltwater in the firn zone of a subpolar ice cap percolates through the firn and snow in both a uniform and a sporadic manner and refreezes to form distinct stratigraphic features. At the top of the Devon Island ice cap some of the meltwater formed in summer percolates uniformly to a depth of less than 0.5 m. This meltwater refreezes within the snowpack that has accumulated since the previous summer. Meltwater also percolates in a very irregular manner down structural features in the snowpack, penetrating well below the depth of general percolation and flowing horizontally wherever there are abrupt changes of snow density or grain size. On refreezing, the meltwater forms ice glands along the vertical channels and ice lenses and ice layers along the horizontal channels; I refer to these as sporadic melt features.

The amount of meltwater that is formed each summer (which can be considered a measure of summer warmth) can be calculated only if the bulk density of the snowpack both before and after melting is known. This is not possible in a core study. Alternatively, one can consider the varying number and thickness, with depth, of both general and sporadic melt features. Unfortunately, the general percolation layer is difficult to distinguish reliably from the surrounding compacted firn at even quite shallow depths, so only the varying amount of sporadic melt features remains as evidence of changing summer climate. In general, the number and thickness of ice layers are proportional to the degree of melting [hence they are found to increase with decreasing elevation on the ice cap (*7*)]. Ice layers are recognizable in the Devon Island ice cap cores to a depth of 150 m, but below this microfractures formed by the drilling process obscure the stratigraphy. The irregular and often massive nature of sporadic percolation, particularly in heavy melt years, complicates any attempt to relate these melt features to climate. Thus, the resolution of a melt event in any one core may be greater than 3 years. The horizontal distribution of sporadic melt features is also very irregular, so that individual features are not always present in all three cores. Therefore, to smooth results and provide a climatically meaningful profile, all three core analyses have been combined to give a single continuous set of mean values at 5-m intervals. Between the surface and 20 m, where the core was unduly affected by melting due to the thermal effect of the drill, the results from three pit and three hand-drilled "dry" cores have been combined, using a weighting procedure dependent on the cross-sectional area of the pit or core examined.

Methods of Study and Results

Cores were photographed over a light table in the field. Pit stratigraphy was either sketched or photographed. Overlays of each photograph or sketch were prepared to increase the contrast between ice and firn. The area covered by ice and firn in each overlay was measured in a Quantimet image analyzer, which works on the gray level principle. To calculate an ice percentage (R) that allows for the different compaction of ice and firn with depth, the area values have been corrected according to

$$R = \frac{0.9S_i}{S_f\rho_f + 0.9S_i} \times 100 \qquad (1)$$

where S_i and S_f are the measured cross-sectional areas of ice and firn, 0.9 is the density of ice (g cm^{-3}), and ρ_f is the den-

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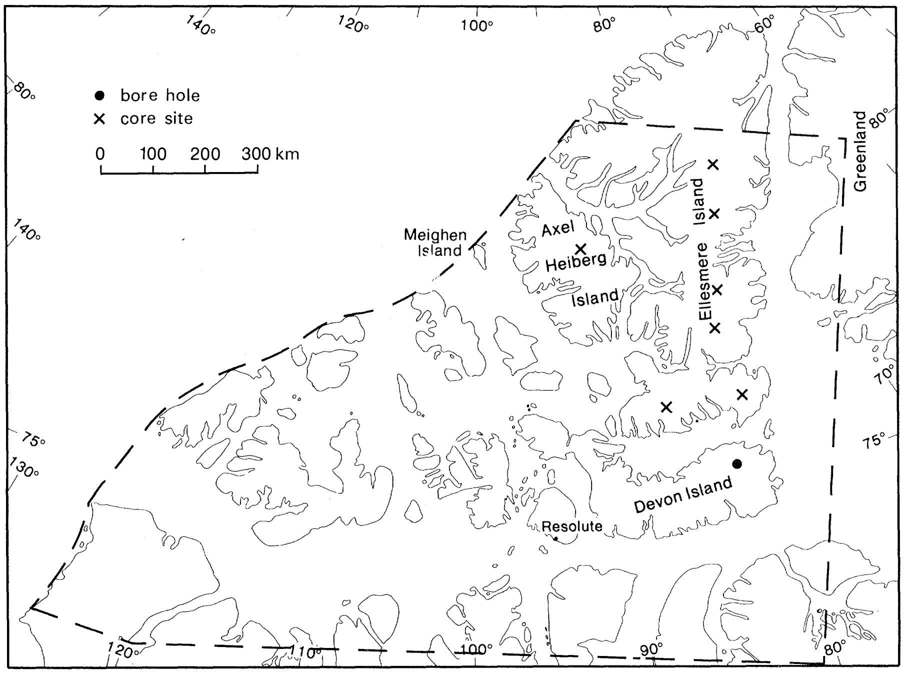

Fig. 1. Queen Elizabeth Islands, Northwest Territories, Canada. The dashed line demarcates the area analyzed for open water.

sity of firn (g cm^{-3}). Below 100 m the firn has developed by compaction into ice with a density of 0.9 g cm^{-3}, so that Eq. 1 reduces to

$$R = \frac{S_i}{S_i + S_f} \times 100 \qquad (2)$$

The results are shown in Fig. 2, where the time scale has been calculated from measurements of the thickness of several annual layers at each of 19 sections in the core between the surface and 220 m. Seventeen of these sections were divided into annual layers on the basis of seasonal variations of dust content (*8*) and one on the basis of seasonal variations of the electrolytic conductivity of the melted firn. The accumulation rate in the surface section is known from annual measurements of the mass balance—that is, the amount of snow that falls on the ice cap minus the amount of snow and ice that melts, divided by the area of the ice cap and expressed as water equivalent. From a knowledge of both the time scale and the vertical strain rate with depth (*9*), it has been calculated that the accumulation rate has been fairly constant over the period of time considered in this article (*10*). This is fortunate as varying accumulation would cause the ice percentage to vary (increasing the accumulation rate and holding the amount of annual melt constant would decrease the ice percentage), which would complicate any climatic interpretation of ice layering.

There are two prominent features in the Devon Island profile in Fig. 2. First, there is an unusually high percentage of ice between the surface and 40 m, which reaches a broad peak between 5 and 20 m. Second, the increment between 40 and 95 m has very few ice layers. The most ice-free part of the whole profile occurs in the lower part of this increment, which was probably deposited during the Little Ice Age, dated here between 1680 and 1730.

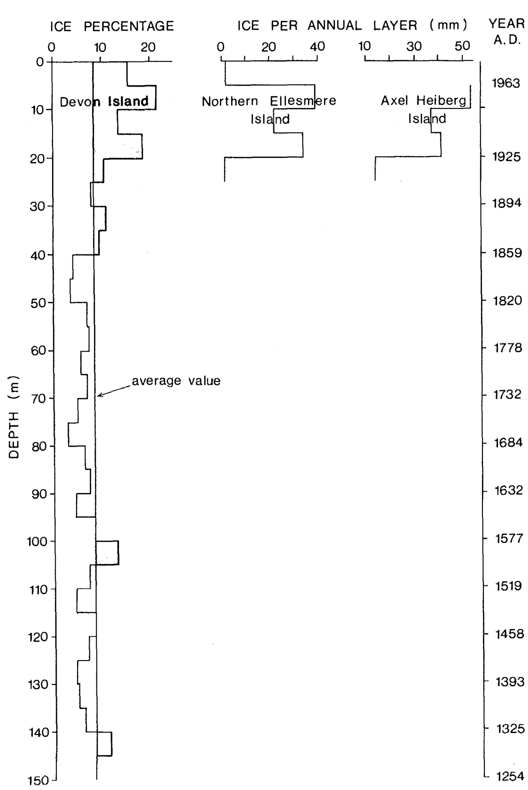

Fig. 2. Ice percentage for the Devon Island ice cap and ice per annual layer for northern Ellesmere Island (*11*) and Axel Heiberg Island (*12*). The time scale on the right ordinate was calculated from measurements of annual layer thicknesses at each of 19 sections of the core between 0 and 220 m (*8*). The values for northern Ellesmere Island and Axel Heiberg Island are plotted as millimeters of ice formed in each annual layer rather than percentages because there is a varying accumulation rate in both sets of data (especially the Axel Heiberg set) which affects the ice percentage. Accurate dating over the entire length of the same section was not possible in the Devon Island ice cap core, so ice percentage values are plotted in this section as in the rest of the Devon profile. The accumulation rate is considered to have been fairly constant over most of the Devon Island profile; this is supported by the good agreement between the three profiles.

Physical Implications

What does this mean in terms of climatic change? The period of melt at the drill-site elevation on the ice cap varies in length each year from zero to 1 or 2 weeks. At first sight, this might be taken to mean that the profile reflects the effects of weather over a meaninglessly short period of time each year. Therefore, to determine how representative ice layering in the core is of summer conditions in general, the amount of ice formed each year in firn deposited from 1961 to 1974 at several points between 1600 and 1800 m above sea level has been plotted against mass balance values for the northwest side of the ice cap for the same years (Fig. 3). As in this case we are considering annual and not long-period variations of melting, the annual ice percentage is not used since it is affected by varying annual accumulation. A 200-m elevation interval has been used to increase the number of sampling points and derive a meaningful average. There is a very high correlation between the mass balance and ice layer thickness in Fig. 3 (correlation coefficient $r = .95$).

Accumulation variations from year to year have very little influence on the mass balance fluctuations of the Devon Island ice cap (*7*). This means that melting is the chief determinant of the mass balance. The high degree of correlation between mass balance and ice layer thickness between 1600 m and 1800 m

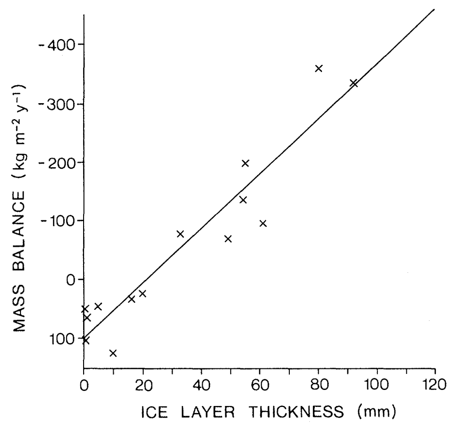

Fig. 3. Mass balance plotted against ice layer thickness (1600 to 1800 m above sea level) on the Devon Island ice cap.

above sea level indicates that the melting/elevation gradient is very similar from year to year.

The important point here is that the ice percentage profile gives a good idea of the past mass balance of the ice cap. From the regression equation for mass balance plotted against ice layer thickness (Fig. 3), it is calculated that the mass balance is zero when ice forms 7.1 percent of the stratigraphy (in terms of water equivalent). The mean ice-layer percentage for the profile below 40 m is very close to this value, suggesting that the ice cap mass balance, at least on the northwest side, was close to zero between about 1300 and 1860. This is not the case between the surface and 40 m, where high amounts of ice give good evidence for the unusual warmth of summer conditions in this century, especially since 1925. This indicates that the northwest side of the ice cap has had a negative balance for the past 100 years. Since 1961, measurements show that the ice cap has lost an average of 59 kg m^{-2} $year^{-1}$; averaged over the entire northwest side of the ice cap, this indicates a surface lowering of about 0.06 m $year^{-1}$.

Heavy ice cap melting since the 1920's is also evident in the stratigraphy of the Ellesmere and Axel Heiberg ice caps (*11*, *12*). Profiles from these ice caps have been analyzed in the same manner as the Devon pits and cores. They show a good agreement with the Devon Island profile (Fig. 2). All three profiles show in detail (not shown in Fig. 2) that there was a large increase in the amount of melting beginning in the mid-1920's. Melting rose to a peak in the 1930's, diminished during the 1940's, and increased again in the 1950's and 1960's.

There has been an apparent decrease in the ice layering in the last 14 years, but the surface section has to be considered with caution. Over the 15 years during which measurements have been made, it has become clear that unusually warm years, such as 1962 and 1969, have dramatic effects on the mass balance and the development of ice layers in the firn zone. Meltwater from the summers of 1962 and 1969 penetrated several years of accumulation and raised the ice percentage over a depth increment greater than 2 m. It is possible that the occurrence of warm summers like these may be one of the chief factors influencing the amount of melting in the firn zone. Thus, a cold period may be chiefly characterized by an absence of such summers and a warm period by an increasing occurrence of them. As far as the uppermost 5 m of the profile is concerned, a warm summer in the next year or two could increase the ice percentage there by deep percolation into the surface layers now at the top of the present profile and eradicate our present "cooling" trend. This is particularly true of the Ellesmere profile, which ends 4 years short of a complete 5-m increment.

Recent work (*13*, *14*) has drawn attention to a cooling trend beginning in the mid-1960's in the Canadian Arctic. Our results do not yield statistically significant evidence for such a trend (*15*). The mass balance and ice layer values in Table 1 show that while there was a short period of cold summers in the mid-1960's, they cannot yet be considered as the beginning of a cooling trend.

So far the ice percentage profile has been related only to conditions on the ice cap itself. It remains to be determined whether the profile reflects changing conditions in areas distant from Devon Island and possibly in the entire Queen Elizabeth Islands area. To do this, the amount of ice formed each year in the firn zone between 1600 and 1800 m above sea level has been related to the maximum area of open water formed each summer in the Queen Elizabeth Channels, $S_{i(n)}$, expressed as a percentage of the total area of the channels, $S_{i(t)}$, as shown in Fig. 1. These data have been extracted from (*16*) and from recent unpublished maps (*17*); they are shown in Table 1 and plotted in Fig. 4. There is a reasonably good correlation between percentage of open water and ice layer thickness (r = .66; P < .01), with significantly large residuals for 1963 and 1969. The correlation improves (r = .73) if we consider the lagged effect of the amount of open water in the preceding year, $S_{i(n-1)}$, according to

$$S_{i(L)} = S_{i(n)} - 0.5\,[S_{i(n-1)} - \bar{S}_i] \quad \text{for all } S_{i(n-1)} \leq \bar{S}_i \qquad (3)$$

where $\bar{S}_i$ is the mean area of open water between 1961 and 1974. This relationship was derived by attempting various systems of weighting. The various weightings showed that a cold summer has less effect than a warm one on the following summer's sea-ice breakup pattern.

Of the two large residuals emerging from the unweighted association between open water and ice layering, one (1963) is substantially reduced by the weighting procedure of Eq. 3, but the other (1969) remains. Apparently the regression analysis has allowed us to determine which summers on Devon Island were dominated by local conditions. The local nature of the Devon Island ice cap summer conditions in 1969, and to a lesser extent in 1963, is confirmed by the stratigraphy of a series of eight cores taken between the surface and a depth of 12 m at the tops of six ice caps on Devon,

Table 1. Open water around the Queen Elizabeth Islands and mass balance and ice layering (thickness of features between 1600 and 1800 m above sea level) on the Devon Island ice cap.

Year	Percentage of total open water	Thickness of ice features (mm)	Mass balance (kg m^{-2} $year^{-1}$)
1961	58.6	55.0	−197
1962	69.8	80.0	−359
1963	52.7	4.4	44
1964	33.9	9.8	125
1965	35.3	0.8	64
1966	46.2	54.0	−135
1967		20.0	25
1968	34.9	0.0	5
1969	41.3	92.0	−332
1970	36.7	16.0	39
1971	50.4	49.0	−69
1972	21.2	0.3	102
1973	56.5	61.0	−95
1974	40.5	33.0	−77

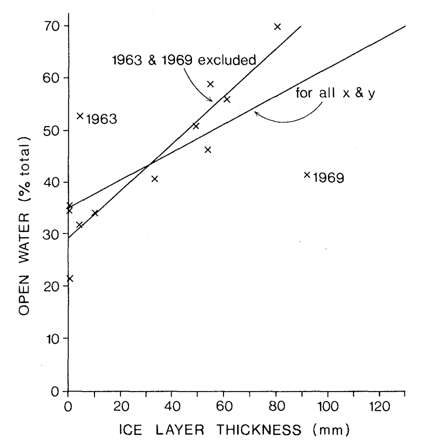

Fig. 4. Maximum percentage of open water between the Queen Elizabeth Islands plotted against ice layer thickness (1600 to 1800 m above sea level) on the Devon Island ice cap.

Ellesmere, and Axel Heiberg islands in 1974 (Fig. 1). The strong melting of 1962 was apparent in all of these cores. Similarly, the distinctly ice-free layers due to the very cold summers of 1964 and 1965 were also common to all eight cores. However, the 1963 layer, which was ice-free in the Devon profile, showed ice layers in several of the other seven cores. The extensive ice layering in the Devon core caused by the warm 1969 summer was not found in any of the seven cores from Ellesmere and Axel Heiberg islands. However, as we have only one strongly anomalous and one slightly anomalous local summer in 14 years, it seems safe to extrapolate the conclusions drawn from our ice ratio profile to the Queen Elizabeth Islands in general. (If 1969 and 1963 are excluded from the analysis, r improves to .93; see Fig. 4.) The large ice caps on Ellesmere and Axel Heiberg islands must have reacted to the cold period in the 17th, 18th, and 19th centuries and the warm period since in the same way as the Devon Island ice cap. Smaller ice caps probably reacted more strongly, growing substantially in the cold period and retreating and often disappearing (*18*) in the present warm one.

Human Implications

The effects of climatic change on human activity in the Arctic are diverse. The indigenous population can be variously affected according to the extent and direction of the change (*19*); a slight cooling can be beneficial to a marine-based economy, whereas a warming may not be. However, any part of the economy that relies on supplies imported from and bulk materials exported to the south is dependent on sea transport. In this respect the ice percentage profile, through its association with sea-ice distribution, leads to some interesting observations. We can see in part why the numerous attempts to forge a northwest passage failed, often tragically, in the 19th century. The various British naval expeditions made their strongest attempts in what the ice profile suggests were some of the coldest summers of the past seven centuries. It was not until the first decade of the 20th century that Roald Amundsen, admittedly with steam power and a ship of shallow draft, took advantage of the early part of the present climatic amelioration to complete the first sailing of the northwest passage. The Canadian S.S. *St. Roche* completed both the first west-to-east sailing and the first negotiation of the passage in a single summer during the even warmer 1940's. Dunbar (*20*) showed that because of ice conditions Baffin Bay was much less open between 1817 and 1870 than between 1952 and 1970. She also showed (*21*) that the spring retreat of ice in the Bering Sea was earlier in the 1960's than between 1870 and 1900. The results of her studies complement those reported here.

Our study provides no firm evidence for any present summer cooling trend (Table 1). However, studies in Greenland (*1*, *6*) show a cooling trend there which is predicted to continue for a few decades. Particular attention should be given to the effect and nature of such climatic change on activities in the North American Arctic.

Summary

Valuable paleoclimatic information can be gained by studying the distribution of melt layers in deep ice cores. A profile representing the percentage of ice in melt layers in a core drilled from the Devon Island ice cap plotted against both time and depth shows that the ice cap has experienced a period of very warm summers since 1925, following a period of colder summers between about 1600 and 1925. The earlier period was coldest between 1680 and 1730. There is a high correlation between the melt-layer ice percentage and the mass balance of the ice cap. The relation between them suggests that the ice cap mass balance was zero (accumulation equaled ablation) during the colder period but is negative in the present warmer one. There is no firm evidence of a present cooling trend in the summer conditions on the ice cap. A comparison with the melt-layer ice percentage in cores from the other major Canadian Arctic ice caps shows that the variation of summer conditions found for the Devon Island ice cap is representative for all the large ice caps for about 90 percent of the time. There is also a good correlation between melt-layer percentage and summer sea-ice conditions in the archipelago. This suggests that the search for the northwest passage was influenced by changing climate, with the 19th-century peak of the often tragic exploration coinciding with a period of very cold summers.

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