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THE STRATIGRAPHIC AND STABLE ISOTOPIC
CHARACTERISTICS OF AN ARCTIC ICING
BYLOT ISLAND, N.W.T.

BY
MARK S. ELVER

A thesis submitted to the Faculty of Science
in partial fulfilment of the requirements for
the degree of Master of Science

Department of Earth Sciences

Carleton University

Ottawa, Ontario

May, 1994

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ABSTRACT

A perennial, glacially fed icing (aufeis), some 0.5 km² in extent, was investigated on Bylot Island, N.W.T. to delineate morphology and formational history. Several boreholes and ice sections were logged to determine icing stratigraphy. Samples were taken in 10 cm intervals along the core length and analyzed for $\delta^{18}\text{O}$ content and electrical conductivity. A maximum icing thickness of 10-11 m was determined by ground penetrating radar, as no section or borehole penetrated to the base of the icing.

The intermittent growth of icings is reflected in the variability of the ice stratigraphy, isotopic signature and conductivity with depth and in area. Five informal "ice types" were outlined to categorize the variations in ice appearance within the icing. These were differentiated from each other based on variations in bubble content and size, ice competency and ice crystallography. Variations in $\delta^{18}\text{O}$ depletion are strongly reflected in the conductivity values suggesting a similar dependence on the rate of freezing during surface water flow and on in situ ice growth. $\delta^{18}\text{O}$ values typically range from -22 ‰ to -25 ‰ except in intervals where a pooling of water is indicated. In this situation, progressive, downward freezing continued to deplete the aqueous phase over time to develop $\delta^{18}\text{O}$ values down to -26.5 ‰ as a maximum depletion. Conductivity is low in all sections, generally less than 50-60 $\mu\text{S}/\text{cm}$ and often below 20. Some isolated layers display values above 100 $\mu\text{S}/\text{cm}$, though this is rare, and the maximum single value obtained from all cores is 170 $\mu\text{S}/\text{cm}$. These low values suggest little or no groundwater input to icing build-up, indicating glacial meltwater as a primary source.

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Chapter 1: Background

1.1 Introduction

The term icing was "first proposed formally by Muller in 1947 to apply to a mass of surface ice formed during the winter by successive freezing of sheets of water that may seep from the ground, from a river, or from a spring" (Carey, 1973). Two other terms are extant in the literature. The Russian term "Naled" and the German "Aufeis", both of which, roughly translated mean "ice that forms on ice" (Carey, 1973).

There is general agreement in the literature that icings are most usefully classified by the source of the icing water. Most authors follow the lead of Grey and Mackay (1979) and Carey (1970, 1973) in subdividing icings into three main categories: river; spring; and ground or seepage icings. Based on work in Spitsbergen, Akerman (1982), has also added pingo, glacier and thermal spring icings to the above list. Tolstikhin (1976) has also classified icings according to size, although this is less common.

Most recent papers (Akerman, 1982; Ashton, 1986; Carey, 1973; Grey and Mackay, 1976; Kane, 1981; Lock, 1990; Sloan, 1976; Slaughter, 1984) on icing formation concur that the initial process involved is "the blockage or constriction of normal flow paths by thermal ice growth or ice debris accumulation (such as frazil ice)" (Ashton, 1986).

If the water flow is maintained throughout part, or all of the freezing period, this constriction to flow causes a gradual increase in the hydraulic pressure upstream of the blockage beneath the ice. When the strength of the blockage is exceeded by the hydraulic pressure, the seal is broken and a sheet of water will pass over the surface and begin to freeze (Carey, 1973).

The individual sheets of water may "range in thickness from a few centimetres to up to half a metre depending on the flow rate of the water. Several flows may travel across the icing body in concert to merge downstream, or distinct separate flows may burst forth independently in time and space. The water flow may also be intermittent or continuous dependent on the degree of hydraulic pressure and the strength of the overburden ice" (Carey, 1973).

As a result, icings develop a characteristic laminar appearance of alternating clear and bubble-rich ice which corresponds to the environmental conditions present upon emergence of the water sheet.

1.2 Purpose of Study

An intensive review of the literature on icings revealed that a minimum of quantitative research has been carried out on the isotopic characteristics of icings, even though the general patterns of icing formation are well documented.

The main objective of this thesis is to outline the stratigraphic and stable isotopic variations of ice formed during the growth of a glacier-related icing. This was accomplished through the examination and correlation of boreholes and sections taken at several sites along the length of the icing over two consecutive years. In

conjunction with this, variations in dissolved solute content (measured by electrical conductivity) over time, and in area, within the icing were also investigated by borehole analysis.

A second objective is to outline potential icing source water variations and isotopic compositions. This was accomplished through background sampling of potential source reservoirs in the area, and by estimating source changes within the icing itself, as indicated by co-isotopic studies (oxygen and hydrogen isotopes).

These investigations were undertaken to provide a detailed analysis of icing processes, upon which future research can be based.

1.3 Previous Work

There exists a fair body of work in the literature on icings and icing related phenomena, although much of the work is repetitive and descriptive. Nearly all the published work on icings has been undertaken by researchers based in the former Soviet Union and in North America. The dearth of articles from other nations enables a grouping of previous efforts into two separate categories: Russian and North American work. Appendix 3 provides a chronological account of previous work undertaken in the field of icing research, therefore, this section will be limited to outlining the major contributions to icing knowledge published prior to the present study.

Up until the early 1970s, research on icings primarily centred on two broad areas of investigation. The first was the development of an observational database noting features such as: icing locations; formation regimes; classification;

stratigraphy and appearance of the ice and the general patterns of icing formation. The second focus of the research was geotechnical in nature, related to icing control, prevention and the effect of icing growth on structures such as buildings and roads. Six landmark papers in the literature provide a full overview of all extant work on the subject up to the mid-1970s. These papers consist of: two annotated bibliographies (Carey, 1970 and Williams, 1965); a comprehensive monograph (Carey, 1973); a symposium (Grey and Mackay, 1979) and two major Russian works (Alekseyev, 1973, and Anisomova, 1973).

Despite the quantity of papers published up to this time, little was known about the processes involved in icing formation outside of the visually apparent style of ice build up and the resultant ice appearance. In 1974, Bari and Hallet published one of the first papers attempting to quantify icing processes. By conducting several cold room experiments (involving the freezing of cylinders of water at various temperatures) the authors determined that the typical layered appearance of icing ice was directly related to the rate of freezing of the individual water layers. This implied a strong connection between ambient air temperature variations and the appearance of icings seen in the field.

In a related paper, Hubbard (1991) quantified the effects of bubble nucleation on the enrichment or depletion of dissolved solids within a freezing water body, and related these processes to the rate of freezing, building on the work by Bari and Hallet. This paper also served to summarize the experiments of several previous studies using similar experimental models.

In addition to this, several researchers in the 1980s and 1990s (Ashton, 1986; Lock, 1990; and Schohl and Ettema, 1986, 1990;) carried out larger scale cold room experiments to determine how icing layers thicken and prograde. This was achieved by continuously discharging water, at a constant source location, along a sloped flume maintained in a sub-zero environment. As freezing progressed, the appearance, extent and physical properties of the resultant ice layers was measured to quantify the formation process of icings that was previously only observed in the field.

A paper published in 1991 by Lozowski quantified the rates of freezing developed when a layer of unfrozen water is discharged over a previously frozen surface. It was noted that the growth of ice occurred at both the upper and lower interfaces of the water body, suggesting that both the substrate and air temperature variations may affect how an icing forms.

Thus, up to the present time, quantitative study has been chiefly carried out on the physical aspects of icing formation such as: how the stratigraphy of icing ice is created; how an icing thickens and progrades; how the individual layers within the icing freeze, and what freezing rates are involved; how the appearance of the individual ice layers is created; and what environmental factors are chiefly responsible for defining these characteristics. Therefore, this study will serve to quantify some of the isotopic properties involved during the formation of icings which have not been discussed in detail within the literature. Chapter 4 (Theoretical Background) will provide a more complete discussion on the details of the physical processes than has been outlined here, in order to fully relate the ground work upon

which this study is based.

1.4 Location of Study Area

Bylot Island is located in the southeast part of Canada's Arctic Archipelago, off the northern tip of Baffin Island (Figure 1). The study area on Bylot Island lies directly across Eclipse Sound (Figure 2) from the community of Pond Inlet.

The icing under investigation is at an elevation of 260 metres above sea level (m.a.s.l.) in a glacial tributary valley trending upslope to the northwest from the snout of Sermilik glacier (Figure 3) and terminating at the snout of glacier B-26, informally known as "Fountain Glacier" (Klassen, 1993). Although icings are found semi-continuously along the entire length of the valley, this present study focuses on a single icing directly adjacent to glacier B-26.

Figure 1: Location Map for Bylot Island (from Klassen, 1993).

Figure 2: An expanded view of the North Baffin Region. The highlighted study area lies across Eclipse Sound from the community of Pond Inlet, N.W.T. The shaded area represents major ice fields (from Klassen, 1993).

Figure 3: An expanded view of the study area illustrating the spatial relationship between Glacier B-26 and "Fountain Icing". Also shown are the outwash valley icings trending towards the lateral moraine of Sermilik Glacier. Nearby glaciers B-28 and B-30 are also shown.

Chapter 2: Methodology

2.1 Field Methods

The field component of the investigation was carried out over July 1992 and June 1993, and a photographic record of the icing for late summer 1991 was made available by the author's supervisor (Dr. Fred Michel). Examination of the icing during the winter months of formation could not be undertaken due to financial limitations and the lack of logistical support available.

Several boreholes were drilled across the body of the icing over both summers using the Stihl-type CRREL ice corer with a 7.5 cm diameter hollow stem auger. Detailed ice descriptions were carried out on all recovered core, noting layer thicknesses, bubble content and shape, ice character within each layer and the presence of any mineral inclusions. A borehole was also drilled in the accumulation area of Glacier B-26 in 1992.

Sampling of the ice core was undertaken in continuous 10 cm intervals along the length of the core, with each interval placed in plastic "whirl-pak" bags on the site, and then promptly transferred into Nalgene polyethylene bottles at the camp upon melting of the ice.

Similar sampling and descriptive work was carried out on several exposed sections of ice at the lateral margins where meltwater channels had eroded downward into the icing. The procedure was the same as that above except that the samples were removed using an ice axe from a prepared wall section.

Grab samples of water were taken of five ice-dammed lakes associated with Glacier B-26, as well as four samples of various surface meltwater streams flowing across the surface of the icing.

During the summer of 1993, an extensive survey using ground penetrating radar (GPR) was conducted over the main body of the icing in conjunction with ground truthing provided by borehole stratigraphy. A grid of baselines and crosslines was established over the icing surface and a program of elevation surveying was undertaken along them in order to eliminate any topographic effects.

A photographic record of the icing, ice core, exposed sections and any discernable processes was also collected during both summers.

2.2 Laboratory Methods

$\delta^{18}\text{O}$ contents were determined for all melted ice samples using CO_2 -water equilibrium at 25 degrees celsius at the Estonian Academy of Sciences Isotope Laboratory in Tallinn and at the isotope facility of the Ottawa-Carleton Geoscience Centre (OCGC). Results are expressed in the per mil notation and are referenced to Standard Mean Ocean Water (SMOW). Reproducibility at the isotope facility in Tallinn is $\pm 0.2\%$ and at the OCGC isotope laboratory the rating is $\pm 0.1\%$ (for one standard deviation). The equipment in the Tallinn facility consists of a Mat 251 mass spectrometer, while the OCGC facility utilizes a triple collector VG SIRA 12 mass spectrometer.

Several selected samples were also analyzed at the OCGC facility for the hydrogen isotopic ratio using zinc reduction at 430 degrees celsius. The hydrogen gas was analyzed on an automated double collector VG 602D mass spectrometer and the results were normalised to SMOW. Reproducibility of these results is $\pm 1.3\%$ (for one standard deviation).

Measurement of electrical conductivity on all samples was undertaken by the author using a platinum-iridium alloy dip cell conductance meter at Carleton University. Reproducibility of these results is rated at $\pm 1\%$.

2.3 Linear Regression

The most common procedure, referenced in the glaciological literature, for the linear regression analysis of covariant data is the Least Squares Method (LSM), which assumes that one variable is known exactly, and that all of the error in the relation can be ascribed to the other variable.

However, in a recent paper by Burn and Maxwell (1993), it was noted that estimates of both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (as examples of covariant data used in this thesis) are subject to error. The authors suggest, therefore, that the Least Squares procedure for determining the "best fit" line for co-isotopic data is inherently inaccurate in its assumptions. Instead, a Cubic Least Squares Method (CLSM) is suggested in order to "minimize more precisely the distances between the data points and the regression line, thus taking into account the error of both variables at each point" (Burn and Maxwell, 1993).

If the error is simply a blanket value based on the precision of the laboratory (as in the case of this thesis) then the CLSM delivers a line known as the Functional Fit Line which is defined mathematically by the formula below:

$$b_f = [((b_L^2/r^2) - L) + (((b_L^2/r^2) - L)^2 + 4Lb_L^2)]/(2b_L^2)$$

Where: b_f = the calculated Functional Fit Slope

b_L = the original Least Squares Slope

r^2 = the r-squared error calculated by Least Squares

L = the ratio of the y-axis sample error/x-axis sample error
(for this study it equals 169.0 based on the lab precision)

The changes in slope from the Least Squares Method to the Functional Fit Method are more or less significant depending on the accuracy of the curve fit, as represented by an increase in the r-squared regression value of the line. An r-squared of 1.0, for example, does not display any alteration in slope from one method to the next as it represents a perfect curve fit through all of the points.

As an example, using a "best fit" line with a slope of 7.63, the change in slope for this line, with an r-squared value of 0.9, would be from 7.63 to 8.11, a significant change. However, if the r-squared value were 0.95, the change would be much less, from 7.63 to 7.85. Although such changes in slope may be quite significant for some of the interpretations of this thesis, as long as only the statistically strong relationships (i.e., those with a high r-squared value) are used in the discussion, significant statistical error should not result. Also, since the LSM is prevalent in the literature, in order to be consistent with previous work on the subject, this method will continue to be used in this thesis.

Chapter 3: Regional Setting

3.1 Physiography

The main physiographic regions of the Eastern Arctic are illustrated in Figure 4 (Klassen, 1993). Both the Davis and Arctic Lowlands physiographic regions exist on Bylot Island.

At the lower elevations, away from the central, ice-covered core, "the sharp, alpine peaks have developed broad, flat shoulders of frost shattered bedrock that slope towards the U-shaped valleys cut into the bedrock by the glaciers of past and present" (Klassen, 1993).

The valley on Bylot Island containing the icing is typical of this physiographic pattern, with lateral meltwater streams incising the Precambrian rocks contained within the valley. At the glacier snouts, icings are formed and braided streams flow within the U-shaped valleys.

3.2 Bedrock Geology

The geology of Bylot Island and north-west Baffin Island is shown in Figure 5 (Jackson, 1975), which is an expanded view of the boxed area in Figure 4. The rocks of the Canadian Shield geologic province on Bylot Island "outcrop largely in the Byam Martin High as a series of nunataks and tors rising out of the central icefield that forms the core of the island" (Jackson, 1975).

The Shield units are of Archean to Alpebian age and are granulite and upper amphibolite metamorphic facies. The rocks consist of "variously banded migmatites and gneiss occupying a north-west plunging synformal structure" (Jackson, 1975).

Figure 4: Physiographic divisions of the North Baffin Region. The boxed area outlines the enlarged view of the study area represented in the geology map of Figure 5 (from Klassen, 1993).

Figure 5: Geology of Bylot Island and Northwest Baffin Island (from Jackson, 1975).

The sediments of the Arctic Platform can be subdivided into two broad regions on Bylot Island. Along the north and west coasts of the island, 8000 feet of Neohelikian strata were deposited in a platform environment influenced by periodic block faulting (Jackson, 1975). These sediments contain a broad range of facies including fluvial sands and gravels, shales and carbonates.

The second suite of rocks consists of 3500 feet of Cretaceous-Tertiary strata contained in the Eclipse Trough of southern Bylot Island (see Figure 5). These sediments consist of a molasse sequence of shales, sandstones and some coal-rich beds (Jackson, 1975).

3.3 Glacial History

A generalized glacial history of Bylot Island is summarized in Figure 6 (Klassen, 1993) showing the major glacial and interglacial periods that have affected Bylot and Baffin Islands in the past.

Interpretation of the geologic evidence used to define native and foreign glacial episodes is almost entirely based on the deposits and landforms of the Eclipse Glaciation as they are the most well-preserved. Earlier and later events are identified by noting differences between their geomorphologic expressions, amino acid ratios and surficial deposits and those of the Eclipse deposits (Klassen, 1993).

The Baffin Glaciation (the oldest visible foreign event to affect Bylot Island) is a collective name for what may have been several events of glaciation occurring prior to the Eclipse period. It is primarily recognized by the occurrence of foreign erratics at a maximum elevation of 1136 m.a.s.l. and glacially derived shells lying

Figure 6: Schematic summary of all foreign glacial events, native glacial events and non-glacial events associated with Bylot Island and northern Baffin Island. The symbols (N) and (F) on the left of the figure indicate Native and Foreign glacial events, respectively. The bar graphs represent sea level at the specified locations (from Klassen, 1993).

inland of Eclipse deposits (Klassen, 1993).

The elevation of these erratics and shells is much higher than any found for the Eclipse Glaciation and higher than many of the mountain peaks. This suggests that a thick regional ice sheet may have invaded Bylot Island, possibly even crossing the topographic divide of the Byam Martin Mountains, prior to the onset of the Eclipse Glaciation (Klassen, 1993).

The next major foreign event on Bylot Island is that of the Eclipse Glaciation which was well preserved by an extensive lateral morainic system found over most of the island at an elevation of 500 m.a.s.l. (Klassen, 1993).

Both the Button and Cape Hatt glacial episodes affected Baffin Island much more than Bylot Island. The only evidence of these events on Bylot Island is the presence of some morainic benches and minor river valleys lying parallel to the south Bylot Island coast (Klassen, 1993).

In addition to the advance of foreign glaciers, there are two distinct episodes of major native advances: Bylot Glaciation and Aktineq Glaciation (Klassen, 1993). During Bylot Glaciation, "mountain ice caps and valley glaciers inundated either most or all of Bylot Island based on the widespread distribution of native crystalline erratics. It is unclear whether these erratics are a deposit of one advance of the native ice or many" (Klassen, 1993).

The Aktineq glacial phase is believed to represent a response to the damming of native ice by the Eclipse ice sheet. It is suggested by Klassen (1993), that the damming of native ice by the foreign ice sheet would result in a much larger volume

of material being stored within the same areal extent of the present day glaciers. Therefore, when the Eclipse event ended, and the foreign ice retreated, the native glaciers underwent a "surge" of expansion beyond the limits seen today. This expansion is surmised to have been short lived and to have extended only to those glaciers in direct contact with the foreign ice. It is best represented in the moraines of Aktineq and D91 glaciers.

At present, it does not appear that the glaciers on Bylot Island have undergone any further advance in the last 5000 years of the Neoglacial period (Klassen, 1993). Most of the large glaciers appear to be either remaining adjacent to or retreating from their terminal moraines (Klassen, 1993).

3.4 Icing Regime

Icings are associated with several physiographic settings on Bylot Island. They have been located near the glacier termini; along meltwater channels at the edges of glaciers or at positions distal to glacier snouts on the outwash of braided glacial streams. The environmental conditions involved in the formation of icings will be outlined in general, and an evaluation will be made among the regimes outlined above, as to why the specific icing under study was chosen for this thesis.

There are three broad factors that govern the formation of icings, which have been grouped by Grey and Mackay (1979): local, seasonal and hydrologic.

The geology and topography of the area in which the icing forms are considered to be the local components. The geology determines the groundwater availability as a source of icing water as well as the distribution of permeable surface

materials that may allow water to flow. Topography determines the hydraulic gradient, and hence the hydraulic head, that is necessary to rupture the icing seal and allow the formation water to flow onto the surface. It also governs the subsequent spread of the water sheet downslope, defining the extent of the icing.

The seasonal components are more complex and varied, as they involve the meteorological characteristics of the icing site. The timing and magnitude of temperature and precipitation variations are considered vital in the formation of an extensive icing.

The hydrologic factors are considered to be a product of a combination of local and seasonal factors, with the groundwater flow regime determined by the amount of precipitation as well as by the local geology and topography.

The icing under study was chosen because it displayed the most favourable set of the above conditions on Bylot Island for a detail examination of an icing. As seen in the air photographic record, Glacier B-26 has remained at its present position for at least the last thirty five years, and possibly for a much longer span of time. This has provided a stable, continuous water source and flow pattern (hydrologic factors) for the development of icings.

The physiography of the icing valley (local factor), as shown in Plate 1, is conducive to stable icing development. The valley is half a kilometre wide and a kilometre and a half long. It is fully constrained on all sides by Precambrian bedrock to the north, diamicton to the south, a large moraine to the east and the snout of Glacier B-26 to the west, which provides a stable water shed for the containment of

Plate 1: Photograph of "Fountain Icing" showing its physiographic relationship to Glacier B-26 and the surrounding terrain, as well as the icing morphology. The icing is 1.5 km long and 0.5 km wide for scale.

valley for extensive icing coverage.

A central core of the icing, over the span of the air photographic record, is preserved although extensive portions of the marginal icing are noted to erode and re-build annually. Figure 7 illustrates a schematic diagram separating the icing into Annual and Perennial sections defined by air photo interpretation and by visual inspection of the extent of erosion in 1992. This situation allows the study of icing growth at the present time in order to outline processes, as well as the investigation of changes in icing development over time.

Other icings on Bylot Island do not appear to display as many of the useful factors outlined above. The icings located in the distal outwash valley of Glacier B-26 (see Figure 3), show extensive coverage of the valley floor (Plate 2a) during icing growth. However, the erosion caused by the braided stream system (Plate 2b) removes the possibility of perennial icings, as well as of correlations of thick stratigraphic units.

Plate 3 consists of a photograph of a meltwater channel icing developed adjacent to Aktineq Glacier (seen in mid-June 1993). Although thick (8-10 m) sequences of icing strata have developed in the constricted (100 m wide) channel, rapid erosion was noted to have occurred in the early summer such that half the icing volume (as shown) had already been removed. Again, large-scale and perennial correlations could not be undertaken.

In summary, "Fountain Icing" was chosen as the study site, as it provided all of the information that could have been gained from a study of other icings on Bylot Island, with the addition of perennial ice investigations and stable, long-term stratigraphic correlations.

Figure 7: Schematic diagram of the area under study showing the approximate separation of the icing into the Annual and Perennial icing divisions. The downstream end of the perennial ice body is estimated from photographic evidence of icing decay.

Plate 2a: Photograph of the outwash valley icings associated with Glacier B-26 that trend towards the lateral moraine of Sermilik Glacier. The valley shown is approximately 5 km long for scale.

Plate 2b: Detailed view of the outwash valley icings showing the typical icing structure, thickness and style of melt. The ice pick shown is 1 m in height.

Plate 3: Photograph of a laterally confined meltwater channel icing located adjacent to Aktineq Glacier to the west of the study area.

CHAPTER 4: THEORETICAL BACKGROUND

4.1 Icing

4.1.1 General Icing Growth

In a series of laboratory experiments, Schohl and Ettema (1986, 1990) investigated the conditions necessary for the initiation and physical development of an icing. They determined that four basic parameters govern the freezing of a body of water in an icing situation: the position along the icing at which freezing is taking place; the degree of spreading of the water; the slope of the frigid base (in this case the flume); and the magnitude of the heat flux to air relative to the latent heat released during freezing (Schohl and Ettema, 1990). Once a complete layer of ice forms on the water surface, two additional parameters must be added: the heat flux to air relative to the heat flux to the frigid base; and the confined width of the freezing water body (which disrupts the two dimensional assumption of the simulation).

In a related work on ice growth, Lock (1990) referred to the data compiled by Schohl and Ettema and provided an excellent qualitative summary of the mathematical treatment used in their study. A cyclic process is shown, in which layers of icing water travel a variable distance down the flume based on a pre-determined rate of water flow, and the geometry of the surface over which the flow takes place (i.e., the flume) (Lock, 1990). Essentially, a dynamic balance is developed amongst the impetus to forward flow of the gradually cooling water (driven by the hydraulic head, slope of the flume and surface tension of the water), and the loss of heat to the

substrate, and the surrounding air striving to freeze the water in place (Lock, 1990).

Part (a) of Figure 8 (Lock, 1990) illustrates the initial development of the first flow of water over the substrate. Soon after emergence, frazil ice platelets, anchored to the base of the flume, begin to grow into the flow of water normal to the surface. This quickly alters the previous laminar flow of the water into flow through a porous media of ice referred to as aufeis slush (Schohl and Ettema, 1990). Over time, the increasing hydraulic resistance of the developing slush, reduces the rate of flow sufficiently to allow the growth of a solid ice layer on the upper surface. This is shown in part (b) of Figure 8.

Gradually the initially thin ice cover extends further downstream (part (c) of Figure 8) until it is extensive enough to re-route the continuing water flow entirely through the layer of slush below. However, as freezing continues, this secondary pathway becomes less permeable until any further movement of water through the first layer is terminated. If the flow is maintained, hydraulic pressure builds near the source outlet until a breach is created in the ice cover and a second layer of water flows over the frozen crust, repeating the process (part (d) of Figure 8).

As each slush channel becomes fully frozen, a characteristic laminar structure, typical of icings seen in the field, develops across the length of the flume. Depending on the amount of time between each flow interval, the laminae consist either of solid ice layers or of alternating slush and ice layers (Schohl and Ettema, 1990). An intermittency in the breakthrough of flow from the source was also noted by Schohl and Ettema. During some portions of the experiment, icing growth could be halted

Figure 8: Schematic diagram summarizing the growth of a 2-dimensional icing in a refrigerated flume (after Lock, 1990).

naturally for extended periods of time while the ice cover became solid and the flow had to be re-directed. In addition, new slush layers were found to extend beyond the previously established downstream end, illustrating an expansion of an icing over time that is often seen in the field.

4.1.2 Single Ice Layer Growth

In a related paper, Lozowski, (1991), carried out a series of experiments in order to quantify the rate of freezing of a flooded ice layer using an insulated water tank (dimensions 158 X 56 X 52 cm). In each experiment, the tank was filled with liquid to 10 cm below the top of the container, placed in a cold room maintained at a constant temperature, and then the liquid was allowed to freeze.

An array of thermistors mounted on an insulated shaft in the middle of the tank measured the temperature of the unfrozen water and the developing ice sheet. The zero degree isotherm was extrapolated over time and depth from the temperature profiles in order to determine the progression of the ice growth at specific times.

Assuming that the substrate over which the water flowed was already frozen, it was determined that freezing occurred from both the upper air/water interface and the lower solid/water interface. The rates of freezing, however, were demonstrated to be different over time at both locations (Lozowski, 1991).

Figure 9 illustrates the initial style of ice growth at both interfaces during the early stages of the experiment. As shown, a linear style of growth was noted at the air/water interface (labelled as upper in the figure) while a square root style of ice

Figure 9: Model predicted growth of the upper and lower ice layers forming during freezing of a layer of liquid flooded on top of an ice sheet (from Lozowski, 1991).

growth was noted for the ice/water interface (lower in the figure). This implies a faster rate of ice growth at the lower interface at the onset of freezing. However, it was noted that the growth rate of the lower boundary ice continually decreased over time, while the upper boundary growth rate remained constant. Consequently, after 2.8 hours of freezing the ice thickness at both interfaces became equal (shown by the intersection of the two graphs in the figure). It was suggested by Lozowski that this decrease in the growth rate of the lower boundary was the result of variations in the heat flux into the underlying substrate.

The upper interface does not display this reduction in growth rate as the heat lost by the freezing water is dissipated into the atmosphere. Over infinite time, the growth rate at this interface was shown to continually decrease from linear growth rates to square root growth rates similar to those of the lower interface at the onset of freezing.

4.1.3 Development of Bubbles in Ice

Bari and Hallet (1974) carried out experiments using an insulated cylinder tank to examine the physical appearance of ice formed by the progressive freezing of a body of water.

These experiments revealed that bubble size, shape and concentration are essentially dependent on the rate of freezing, the amount of dissolved air in the water and the degree of particulate content available for use as nuclei. It was determined that several, distinct fields of bubble shapes and sizes develop depending on the velocity of the ice growth alone, if a specific sample of water is selected. Table 1

summarizes the appearance of the ice in each of the growth rate fields.

Essentially, at the slowest growth rates, the ice is clear and bubble free and may develop large crystals with an elongate, and visible, hexagonal form if the water is left undisturbed. At mid-range growth rates, large, centimetre-sized cylindrical and egg-shaped bubbles develop, which tend to be isolated in an otherwise clear ice body. At the fastest growth rates, numerous millimetre-sized, spherical bubbles dominate the ice body, reducing the clarity to the point of producing an almost "milky" haze at the most rapid rates.

Freezing Rate X ($\mu\text{m/s}$)	Ice Appearance
$X > 25$	Abundant 1 - 2 mm sized egg-shaped and spherical bubbles creating an opaque ice appearance
$5 < X < 25$	Mixture of 2 mm sized egg-shaped bubbles and 5 mm sized cylindrical bubbles. As freezing rate decreases cylinders become more numerous until at 5 $\mu\text{m/s}$ they are the sole bubble type
$3 < X < 5$	Cylindrical bubbles increase in size ($> 1 \text{ cm}$) but display less bubble volume, becoming isolated in an otherwise clear ice body
$X < 3$	Clear, bubble free ice with no visible crystal structure

Table 1: Variations in ice layer appearance as defined by freezing rate

4.1.4 Stable Isotopes

The relative concentrations of the heavy (^{18}O and ^2H) and light (^{16}O and ^1H) isotopes in a given sample of water are generally expressed in terms of their "del" (δ) value (expressed in per mil notation). This value represents the difference between the isotopic ratios in the sample, and the isotopic ratios of a standard called Standard Mean Ocean Water (SMOW). The calculation of the δ value is shown below for oxygen:

$$\delta^{18}\text{O} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}} - (^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}}{(^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}} \times 10^3$$

A similar calculation can be performed for hydrogen.

During condensation of water vapour into precipitation, the heavy isotopes are preferentially enriched in the non-vapour phase (Dansgaard, 1964). As a result, the δ values for natural fresh waters vary depending on the evaporation-condensation history it has undergone. By analyzing samples of precipitation from numerous sites across the globe, Craig (1961) developed a consistent linear relation expressed as:

$$\delta^2\text{H} = 8 \delta^{18}\text{O} + 10$$

This relation, known as the Global Meteoric Water Line (GMWL), relates the isotopic composition of precipitation at a given site to the global range of possible values. The relation produces a line with a slope of eight when plotted on a $\delta^{18}\text{O}$ - δD co-isotopic graph. To more closely approximate isotopic compositions of precipitation for a specific region, Local Meteoric Water Lines (LMWL) are also

calculated using local water samples.

In addition, the preferential condensation of the heavy isotopes in precipitation is dependent on the ambient air temperature at which condensation occurs (Dansgaard, 1964). This results in a successive depletion in the δ values of precipitation, with an associated decrease in condensation temperature. Thus, a moist air mass moving towards colder regions will produce progressively more depleted δ values in the precipitation falling from it (Dansgaard, 1964). This will also occur as an air mass increases in altitude, the air temperature becoming increasingly lower. This "Altitude Effect" results in a progressive depletion of precipitation falling on mountain or glacier slopes that display significant elevation.

The use of stable isotopes in research involves the understanding of several kinetic processes that can cause fractionation in the δ values of a given sample of water during phase changes. The following section will outline the relevant isotopic processes that may be involved in determining the isotopic composition of the icing under study.

The most important fractionation process encountered in the formation of icings is known as the "freezing effect". Numerous papers in the literature (Hubbard, 1991; Lehmann and Seigenthaler, 1991; Majoube, 1971a, b; Michel, 1982, 1986; Michel and Fritz, 1982; O'Neil, 1968; Posey and Smith, 1957; Souchez and Lorrain, 1991; and Suzuoki and Kimura, 1973;) have shown that during a single episode of freezing, the heavy isotopes of oxygen and hydrogen are preferentially incorporated into the solid phase at the expense of the liquid phase. This causes a positive shift

in the isotopic composition of the solid phase and a resultant depletion in the unfrozen portion. By repetition of this fractionation process during subsequent freezing events, the remaining bulk water isotopic signature becomes continuously more depleted over time, which is reflected by a negative isotopic shift in the ice fraction.

Figure 10 illustrates this effect on an initial sample of SMOW water. As shown, during the first stages of progressive freezing, the ice becomes enriched in heavy isotopes compared to the initial bulk water composition (see point $k = 0.1$ on the plotted line). As freezing continues (represented by an increase in the k values on the line), the isotopic composition of the ice continues to shift toward the composition of the initial water along a stable slope. When 66 % of the water is frozen, the isotopic composition of the ice is shown to be equal to the initial water composition. As freezing continues, the ice actually becomes more depleted in heavy isotopes than the initial bulk water (Souchez and Lorrain, 1991). The slope of this "freezing line" is dependent on the initial isotopic composition of the bulk water, with a greater slope indicating a less depleted initial source water.

Lehrmann and Siegenthaler (1991) have recently completed experimental work relating the apparent fractionation factors that govern the "freezing effect" to the rate of freezing of an ice layer. Figure 11 demonstrates that the amount of fractionation varies during a given freezing event, depending on the rate of freezing. The two graphs in the figure (upper for oxygen, lower for hydrogen) show a progressive reduction in the amount of fractionation with an increase in the freezing rate. The

Figure 10: Illustration of the changes in δD values noted in ten successive fractions of ice formed by the progressive freezing of a sample of SMOW water (from Souchez and Lorrain, 1991).

Figure 11: A graphical illustration of the apparent fractionation constant $E_{app} = E_{app} - 1$ as a function of the freezing velocity in an ice layer for $^{18}\text{O}/^{16}\text{O}$ (top graph) and D/H (bottom graph) stable isotopic ratios (from Lehmann and Seigenthaler, 1991).

maximum fractionation factor (which represents equilibrium conditions) is shown where the lines intersect the y-axis, that is, where the freezing rate is zero. For the oxygen isotopes, the equilibrium value is shown to be 2.91 ‰. For the hydrogen isotopes, the equilibrium value is shown to be 21.2 ‰.

A second fractionation process is known as the "Evaporation Effect". If natural waters are affected by a high rate of evaporation relative to the amount of fresh water inputs, the isotopic compositions deviate off the meteoric water line by a linear relationship expressed as:

$$\delta^2\text{H} = 5 \delta^{18}\text{O}$$

where: $\delta = \delta_{\text{sample}} - \delta_{\text{freshwater}}$

This relation aligns evaporated samples of water on a best fit line with a slope of five when plotted on a $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram.

A final process that can affect the isotopic composition of ice is the physical mixing of bulk waters with varying isotopic compositions. The resultant bulk water composition will represent a weighted mean of the isotopic values of all the components assuming sufficient mixing can occur.

4.1.5 Electrical Conductivity

Another process that occurs during the freezing of water is the expulsion of electrolytes, air bubbles and non-electrostatic particulate matter before a slowly advancing freezing front (Corte, 1962; Clayton, 1990; and Rewell and Dillon, 1972; all in Hubbard, 1991). This will progress during continued, slow freezing until the

nucleation of bubbles is initiated. The sudden reduction in the concentration of dissolved gases raises the freezing point of the liquid, resulting in a rapid increase of the freezing rate (Hubbard, 1991). This effectively traps any dissolved solutes, along with the bubbles, in the newly formed ice as there is insufficient time for the migration of these elements into the adjacent water. This implies that the concentration of solutes is also governed by the rate of freezing, similar to the concentration of bubbles shown previously.

Also, if freezing progresses from both upper and lower interfaces, the unfrozen water in the centre will become progressively more concentrated in dissolved solids over time. This enrichment will continue until the last ice layer to form freezes the cumulative solute content in place. The final ice layer thus displays elevated conductivity values, while the surrounding layers display lower conductivities, compared to the original, unfrozen water content.

If the rate of ice growth is sufficiently fast, solutes are unable to be expelled before the advancing freezing front (Hubbard, 1991). Thus, any solute concentration present in the ice at a given location displays conductivity values close to the original bulk water content at that location.

4.2 Glacier

4.2.1 Altitude Effect

The altitude effect for Glacier B-26 is calculated in this section. The snow samples taken from the accumulation area of the glacier were collected at an elevation of 1550 m above sea level (a.s.l.). Table 2 illustrates the water equivalent precipitation values (in millimetres), by the month, and the co-isotopic composition, by the month at Pond Inlet, which is at an elevation of 46 m a.s.l.. By calculating the difference between the weighted mean isotopic composition of the glacier snow (found in Appendix 1) and the weighted mean isotopic composition of Pond Inlet, an altitude effect can be estimated by the difference in elevation between the two sites.

The weighted mean $\delta^{17}\text{O}$ composition for Glacier B-26 in the accumulation area was calculated to be - 27.5 ‰, while the weighted mean $\delta^{18}\text{O}$ composition for Pond Inlet was - 25.1 ‰. This indicates that there is a 2.4 ‰ difference in $\delta^{18}\text{O}$ isotopic composition between the altitude at Pond Inlet and the accumulation area, which corresponds to an altitude effect of - 0.16 ‰/100 m change in elevation. This value is similar to calculated altitude effects for snow in Norway of - 0.2 ‰/100 m by Ambach and Dansgaard (1968), which has a similar climate and latitude to Bylot Island.

A rough approximation of the altitude effect for hydrogen can also be calculated. Table 3 shows the co-isotopic compositions for the top forty centimetres of accumulation snow and the depth intervals sampled. Calculation of the weighted

Month	Year	Deuterium	Oxygen 18	Water Equivalent (mm)
July	1990	-153.0	-22.9	55
Aug.	1990	-153.0	-19.2	33
Sept.	1990	-157.0	-20.8	42
Oct.	1990	-191.0	-25.7	30
Nov.	1990	-287.0	-37.4	18
Dec.	1990	-281.0	-37.0	5
Jan.	1991	-338.0	-43.6	10
Feb.	1991	-278.0	-35.6	11
March	1991	-210.1	-27.6	12
April	1991	-233.4	-32.1	18
May	1991	-163.6	-20.0	15
June	1991	-158.4	-21.3	30
July	1991	-126.9	-17.6	55
Aug.	1991	-168.7	-23.0	33
Sept.	1991	-173.8	-23.0	42
Oct.	1991	-176.2	-23.9	30
Nov.	1991	-225.8	-29.4	18
Dec.	1991	-300.5	-39.5	5
Jan.	1992	-321.1	-41.0	10
Feb.	1992	-325.0	-40.9	11

Table 2: Precipitation amounts by the month and co-isotopic compositions by the month for several years of precipitation at the location of Pond Inlet, N.W.T.

Snow Depth (cm)	Deuterium	Oxygen 18
5	-173.3	-23.0
10	-188.8	-25.4
15	-173.7	-24.0
20	-170.8	-23.2
25	-165.6	-22.4
30	-186.5	-24.6
35	-193.1	-25.8
40	-189.6	-25.5

Table 3: Co-isotopic composition by sampling interval for a series of selected samples taken from the accumulation area drillcore.

mean for the selected samples alone, result in an isotopic composition of -24.0‰ for oxygen and - 178.6 ‰ for hydrogen.

Since a discrepancy exists between the oxygen value of the selected samples and that for the entire drillcore, it can be inferred that the hydrogen value for the selected samples is also unrepresentative of the drillcore. However, since the difference between the two oxygen isotopic values is known, the hydrogen isotopic composition for the drillcore can be inferred from the known value of the selected samples. This results in a $\delta^2\text{H}$ composition of - 204.7 ‰ for the drillcore, translating into an altitude effect for hydrogen of - 1.12 ‰/100 m change in elevation. This assumes that the changes in oxygen isotopic composition from the top 80 cm to the deeper drillcore are matched by equal fractionations in the deuterium composition and, therefore, it is a rough estimate.

4.2.2 Superimposed Ice

Superimposed ice in arctic and alpine glaciers, as described by Koerner (1970, 1973) involves the formation of pure ice layers within an otherwise pristine layer of glacier snow.

Surface melt or rain water percolates through the unconsolidated snow horizons until it refreezes "within or at the base of the yearly surface balance snow layer" (Koerner, 1973). The passage of this meltwater through a recrystallizing snowpack causes an isotopic enrichment in the snow horizons, at the expense of the percolating fluid, due to solid-liquid fractionation processes. Thus, the meltwater, or rainwater, once refrozen, displays an isotopic signature that is more negative than the

original composition (Koerner, 1973).

The final isotopic signature of the depleted ice layers, and the relatively more enriched snow horizons between them, actually represents "a varying relationship between the original δ value of the melted snow cover (or rainwater), and the final δ value of the superimposed ice layer" (Koerner, 1973). This is further complicated by the isotopic enrichment of the solid phase during the process of meltwater percolation. It is also dependent on whether sufficient melting occurs in a given year to have an isotopic effect (Koerner, 1973).

4.2.3 Glacial Hydrology and Ice-dammed Lakes

Glacial Hydrology

The nature of arctic and alpine glacial hydrology typically consists of a series of englacial and subglacial tunnels as described in several papers in the literature (Collins, 1979; Collins and Young, 1979; Hooke, 1989; Johnson, 1991; Kasper and Johnson, 1991; Nye, 1976; and Shreve, 1972;).

The englacial system is thought to consist primarily of "an arborescent network of passages with numerous millimetre-sized, finger-tip tributaries joining downward into ever larger conduits" (Hooke, 1989). The subglacial system is thought to be "a tortuous system of linked cavities transected by a few relatively large and comparatively straight conduits" (Hooke, 1989).

It is theorized that the form and continuity of these conduits changes over time as glacial movement and overburden pressure close abandoned tunnels. In a 1976 paper, Shreve noted that glacial conduits also could be sealed effectively by ice

debris carried through the system or by subglacial sediment squeezed into the conduits by glacial overburden pressures. New tunnels are thought to open by the continuously shifting meltwater flow patterns and the associated thermal melt (Hooke, 1989).

Ice-dammed Lakes

An associated factor that is often involved in discussions of glacial hydrology is the water discharge associated with the drainage of ice-dammed lakes. This is relevant for this study as several ice-dammed lakes are associated with Glacier B-26 in the study area. Figure 12 illustrates the position of these lakes, relative to Glacier B-26, as well as their oxygen isotopic compositions.

Numerous references in the literature (Gilbert, 1971; Hooke, 1983a; Johnson, 1991; Mottershead and Collin, 1976; Ostling and Hooke, 1986; and Russell, 1989) cite examples of subglacial water storage and the draining of ice-dammed lakes as sources of glacier runoff.

It was hypothesized (Russell, 1989) that in order to initiate drainage of an ice-dammed lake, a threshold hydraulic pressure head must be generated such that the edge of the glacier ice abutting against the lake can be "floated" by the lake water. This is believed to be accomplished by a rising lake level caused by summer melt inputs to the basin. This in turn, creates an initial opening for water movement to begin. Although this opening may exist, it was further postulated that lake drainage can only occur if there is a sufficient hydraulic gradient from lake to outlet, to initiate a steady flow of water. In addition, an open connection to the glacial drainage system

must exist for the initiation of flow, unless the lake is near the edge of the glacier and can simply flow out after uplift (Hooke, 1989).

During the summer, inputs into the volumetrically restricted tunnels and channels within the glacier are typically high. This results in the development of sufficient hydraulic pressure in the conduits to prevent the necessary gradient for lake discharge. However, during the winter, the inputs become sealed due to freezing and shut-down of the meltwater flow, resulting in a reduction of the hydraulic pressure in the tunnels. Thus, the hydraulic gradient within the tunnels becomes more pronounced, and lake drainage can be initiated.

In addition, summer inputs into the lake basins increase the hydraulic head of the lakes to a maximum in late summer/early fall. This increases the amount of uplift in the glacier dam adjacent to the lake as the glacier begins to freeze back, increasing the likelihood of drainage.

Figure 12: An expanded view of the study area showing the locations and $\delta^{18}\text{O}$ isotopic composition of four ice-dammed lakes adjacent to Glacier B-26.

Chapter 5: Results/Discussion

5.1 Ice Descriptions and Terminology

The stratified nature of the icing structure requires a systematic means of visually distinguishing one ice layer from another in the field. To accomplish this, a classification scheme for various ice types was developed by the author.

Three criteria were utilized to separate the icing strata into these various "ice types": the degree of competency; the bubble content, size and shape; and a rough estimate of the ice crystal structure. Based on these criteria, the stratigraphy of the icing ice was separated into five categories: Candle ice; Snow ice; Bubble-rich ice; Clear ice and Milky ice. The characteristics of each type are outlined in Table 4.

Plate 4 illustrates a typical example of Candle ice, showing the well defined crystal habit. An example of the spatial relationship between different ice types in a section of icing core is illustrated in Plate 5.

A thorough study of the icing types described in Table 4 shows a strong relationship to the experiments outlined by Bari and Hallet (1974), discussed previously. Although growth rates on Bylot Island may, in reality, be different from those in the experiments, the trends of bubble growth proposed by these authors appear to be represented in the cores taken from the icing under study. Snow ice is not included in this discussion as it is not formed by the freezing of a water layer, and therefore, will not follow the freezing rate characteristics outlined for the other ice types.

Ice Type	Ice Description
Candle Ice	Visible, hexagonal ice crystals with columnar form. Occasional > 5 mm sized tubular bubbles may be developed along crystal edges or at terminations in an otherwise clear ice body (Adams, 1976).
Bubble-Rich Ice	Informal term. Mixture of 1 - 2 mm sized spherical bubbles with centimetre sized cylindrical bubbles in an otherwise clear ice body. The bubble content is highly variable but not as high as Milky ice.
"Snow" Ice	Loosely-packed, low density and unconsolidated ice possessing a granular texture and numerous 1 mm sized spherical bubbles creating a white haze (defined in Adams, 1976 and Knight, 1962).
"Milky Ice"	Informal term. Visually similar to "snow" ice, however, this ice is fully consolidated and competent and is separated from it on that basis.
Clear Ice	Informal term. Competent ice layer with no bubble content. Separated from Candle Ice as there are no visible ice crystals.

Table 4: Icing ice descriptions related to a set of five informal "ice types" outlined by the author. Relevant references for classical ice descriptions are also included.

Plate 4: Photograph of a sample of Candle ice taken from drillcore collected in 1993. The columnar nature of the ice, as well as its low bubble content, is apparent in the photo.

Plate 5: Photograph of a variety of icing ice types from a borehole drilled in 1993 showing how the bubble content and layer thickness varies with depth.

Scale (cm)

It can be inferred that the range of ice types encountered in the icing represents a series of growth rates. The $> 25 \mu\text{m/s}$ style growth in the Bari and Hallet experiment produces characteristics similar to that seen in Milky ice, making this style of ice formation a rapid growth rate end-member. The mid-range mix of bubble shapes and sizes, showing varying rates of cooling, can be seen to produce the Bubble-Rich ice. The very slow growth rates of less than $3 \mu\text{m/s}$ make Clear ice the final end member. Candle ice can be inferred to have even slower growth rates (closer to $1 \mu\text{m/s}$) where single large crystals, with vertically oriented c-axes, were formed (Bari and Hallet, 1974). Thus, Candle ice is the true slow growth end member, but it only occurs under very limited conditions. The research conducted on lake ice indicate that Candle formation requires a fairly stable "ponding" environment for c-axis growth to remain undisturbed.

5.2 Isotopic Characteristics of the Icing Source Water

There are two main possibilities that could exist to account for a constant water source during the winter freeze-up of surface runoff. Either glacial meltwater is stored within englacial or subglacial conduits and maintained in an unfrozen state, or, the ice-dammed lakes adjacent to the glacier either periodically or continuously drain through these same conduits during the period of icing formation.

Most of the published work on ice-dammed lake drainage deals with catastrophic drainage leading to floods of a large magnitude. This style of lake drainage may be responsible for the large portions of the icing that are seen, on the air photographic record, to have been eroded away in the past. As shown in Figure 13, the air photographs for 1958 and 1982 indicate that the icing did not exist adjacent to Glacier B-26 in the past, but was actually eroded back to a position further downstream. It is possible that previous catastrophic floods associated with these lakes were responsible for the melt of these portions of the icing in the past. Further evidence of past drainage can be seen in Lake 5 (Figure 12), which was noted in the field to display several raised beach positions indicating that the lake level was several metres higher in the past than at present. However, this does not explain how the annual cycle of icing build-up can occur with regularity and stability, as a catastrophic flood would erode rather than build even thick portions of icing.

The numerous layers displayed in the icing strata indicates either periodic or slow continuous flow and not a catastrophic rate. Thus the existing relationship between Glacier B-26, the associated lakes and the icing under study may represent

Figure 13: Detailed schematic diagram of the icing under study showing the locations of all boreholes and sections drilled during the summers of 1992 and 1993. Borehole numbering shown here corresponds to appropriate ice section figures in the text. The age labels shown next to the icing limit represent previous positions of the icing eroded back from the present day glacier/icing contact.

a dynamic equilibrium amongst drainage patterns, conduit continuity and freezing of the escaping water. An intermittent flow in the icing formation waters could be generated by the sealing of a particular conduit, and the subsequent transfer of water to another conduit. Also, the low temperature of the lake water on Bylot Island would not provide large amounts of excess heat with which to expand the size of the conduits to catastrophic flood size. This may increase the stability of the system as the meltwater must expend most of its heat to maintain a liquid state rather than to instigate ice decay.

Meteoric Water Line Genesis

If the source water for the icing consists of mixed ice-dammed lake and glacial meltwater sources, a means must be found to take both of these factors into account when determining the bulk meltwater properties of the source water for the icing.

Table 5 illustrates the co-isotopic compositions measured for the ice-dammed lakes, meltwater streams and several selected samples of icing ice taken from various depth intervals and boreholes across the icing. These are graphically represented in Figure 14, along with the selected accumulation area samples discussed earlier. The LMWL generated for the Pond Inlet precipitation values is also shown in Figure 14.

As shown in Figure 14, all of the icing, ice-dammed lake and meltwater stream samples plot off the meteoric water line determined for Pond Inlet, as do the majority of the glacier snow samples from the accumulation area. However, the slope of the best fit line for the accumulation area snow samples is the same (8.0) as that for the Pond Inlet precipitation samples. This suggests that the range in δ values

Figure 14: A co-isotopic plot of the "Fountain Icing" selected samples, the accumulation area snow, the meltwater streams and the ice-dammed lakes. The local meteoric water line for Pond Inlet is also shown.

Sample	Deuterium	Oxygen 18
Lake 2	-184.2	-23.5
Lake 3	-183.7	-24.5
Lake 4	-182.6	-24.0
Lake 5	-183.2	-23.8
North Stream	-178.7	-23.6
Centre Stream	-190.5	-24.8
North Stream 2	-177.8	-23.5
South Stream	-184.0	-24.7
Glacier Snow	-204.7	-27.5
Overall Avg.	-185.5	-24.4

Table 5: Co-isotopic compositions of the average accumulation area snow, ice-dammed lakes and meltwater streams associated with Glacier B-26, Bylot Island, N.W.T.. The overall average of these samples is also provided at the bottom of the table.

Isotope Source	Deuterium	Oxygen 18	Freezing Slope
Least Depleted	-174.0	-23.2	5.97
Mid Depleted	-191.0	-25.2	5.86
Most Depleted	-205.0	-27.2	5.77
Glacier Avg.	-185.5	-24.4	5.89
Overall Avg.	-188.9	-25.0	5.91

Table 6: Calculation of the average freezing slope using three original, bulk water co-isotopic compositions of Bylot Island glacier ice taken from Souchez and Lorrain (1991), as well as, the mean isotopic value calculated for the accumulation area of Glacier B-26 (Table 5).

for both sample sets are solely dependent on the condensation isotopic effects outlined previously (i.e. there are no kinetic effects occurring to alter the slope of the precipitation relation in either case). But, the intercepts of the two relations are distinct and separate, indicating a shift in the δ values of the accumulation area snow to a more depleted signature than those values following the Pond Inlet meteoric water line.

This shift may be produced by a change in the bulk isotopic properties of the moist air masses from which the glacier and Pond Inlet precipitations originate. The similar slopes indicate similar processes, but the disparate intercepts suggest that a consistently more depleted water source is being condensed, overall, at the accumulation area than at Pond Inlet. This change in water source may result from two distinctly different moist air masses following unique condensation histories, or by the altitude effect depleting the same moist air mass coming from Pond Inlet, as it rises over the intervening mountains, prior to deposition of the glacier snow.

Whatever the cause of the isotopic shift, the precipitation line for Pond Inlet does not appear to be a valid approximation of the initial source water isotopic compositions forming the icing. Therefore, a new meteoric water line must be generated that does represent the typical source water outputs.

Precipitation at the various elevations between the icing and the accumulation area must represent the primordial source for all of the possible inputs to the icing, either as surface snow melt or melt inputs coming from the glacier ice itself. Since this is the case, all of the ice-dammed lake, meltwater stream and accumulation area

isotopic compositions must represent examples of this precipitation along the entire range of possible elevations.

A sum of the co-isotopic compositions shown in Table 5, as well as the overall average for the accumulation drillcore results in an isotopic average value of -24.4‰ for oxygen and -185.5‰ for hydrogen. The average value for the entire drillcore was used in order to incorporate as much of the accumulation area snow values, over as many possible years of accumulation, as possible. This average isotopic value can be seen to represent a bulk approximation of the range in altitude-related inputs that may form the icing.

However, in order to generate a meteoric water line for these inputs (and therefore the initial source values for the icing ice), an appropriate slope must be taken through this average value which accurately represents a more complete range of the possible precipitation values for Glacier B-26. Figure 15 illustrates a co-isotopic plot (Souchez and Lorrain, 1988) of several samples of glacier ice taken from three other Bylot Island glaciers (Aktineq, "Camp" and Sermilik) near glacier B-26. The best fit line through these points results in a well-constrained meteoric water line with a slope of 7.63. This very strong correlation in isotopic values from all three separate glaciers implies that there is very little variance in the isotopic composition of the ice from one glacier to another. This may also be the case for glacier B-26, which shares a common accumulation area with the other three glaciers.

Figure 15: Two graphs illustrating the Least Squares regression curve fits calculated for co-isotopic plots of samples of glacier ice (slope of 7.63) and basal ice (slope of 4.9) taken from Aktineq, "Camp" and Sermilik glaciers (from Souchez and Lorrain, 1991). The open symbols refer to samples from Sermilik Glacier, the black symbols refer to Aktineq Glacier and the black and white symbols refer to "Camp" Glacier.

If this meteoric water line represents a valid best fit for glacier B-26, the average isotopic value calculated above (-24.4‰ for oxygen and -185.5‰ for hydrogen) should plot on the 7.63 slope generated for the other glaciers in the vicinity. As shown in Figure 15, this value does plot on this meteoric water line, suggesting that this best fit is also representative of Glacier B-26 ice. Therefore, the range of possible source water isotopic compositions can be represented by this meteoric water line with a slope of 7.63, passing through the average value calculated above.

Freezing Slope Calculation

In order to relate the freezing effects of the icing to the calculated meteoric water line, a freezing slope must be determined for the fractionation. As stated in Souchez and Lorrain (1991), the freezing slope is essentially related to the initial isotopic composition of the bulk water prior to freezing, as long as the isotopic value of new inputs into the system are not significantly different from the initial bulk water. This assumption must be made for the icing under study as there is no definitive information on the fluctuations of source values during icing freezing.

The following equation, taken from Souchez and Lorrain (1991), defines the calculation of freezing slopes under the conditions stated above, namely an open system situation with little fluctuation in the isotopic composition of inputs after the onset of freezing:

$$\text{Slope} = [a((a-1)(1000+H_i))] / [b((b-1)(1000+O_i))]$$

where: a = fractionation co-efficient for Hydrogen (1.0208)

b = fractionation co-efficient for Oxygen (1.003)

H_i = Initial source composition of Hydrogen

O_i = Initial source composition of Oxygen

Table 6 displays freezing slopes calculated for three co-isotopic values taken from the meteoric water line of the Souchez and Lorrain paper (a mid-range isotopic composition, the most depleted sample and the most enriched sample) as well as for the average co-isotopic value calculated for glacier B-26. As seen in the table, the variance in the freezing slopes for the range in the glacier ice isotopic compositions, is limited to a maximum change of 0.2. An average freezing slope of 5.91 was calculated from these values, which is also shown in Table 6. Due to the small range of freezing slope values, the average value of 5.91 will be used for the icing ice samples when discussing freezing effects.

5.3 Overall Icing Isotopic Trends

As a whole, the selected icing ice samples illustrated in Figure 14, form a best fit line with a slope of 6.96 and a regression value of 0.82. The relatively poor relationship between the samples is most likely a result of the variable degree of freezing effect present from one sample interval to another.

Figure 16 illustrates a co-isotopic plot showing the separation of the icing samples into Perennial and Annual fields of composition. Although there is significant overlap between the two groups, there is a slight. The Annual icing appears to be less depleted overall than the Perennial samples.

Figure 17 separates the borehole data according to growth rate, with fast to moderate growth (Milky to Bubble-Rich ice) as one subgroup and slow growth rate ice (Candle ice) as a second subgroup. The Milky ice intervals are labelled in the figure, and the local meteoric water line is also shown.

The Milky ice intervals universally plot on the LMWL, which implies that none of the samples have undergone fractionation during freezing, probably because the growth rates associated with this ice type are too fast to allow fractionation to occur. Therefore, any differences in isotopic composition in the formation of these ice types appears to be due to the mixing of isotopically distinct source waters.

The Bubble-Rich ice appears to display some fractionation within some intervals, while others plot directly on the LMWL. Since Bubble-Rich ice displays similar visual characteristics for a broader range of freezing rates than any other ice type, it should not be surprising that some plot on the meteoric line while others may

Figure 16: A co-isotopic plot separating the Annual and Perennial icing samples. The local meteoric water line for Glacier B-26 is shown.

Figure 17: A co-isotopic plot of the Candle ice and Milky/Bubble-Rich ice as indicators of growth rate differences, referenced to the glacier B-26 local meteoric water line.

plot on a freezing slope.

The Candle ice intervals in Figure 17 display a broad scatter of values along the entire range of the meteoric water line. This suggests that both significant variations in source, and freezing effects, are present in all of the samples. Some Candle ice layers do plot on or adjacent to the meteoric water line which may indicate that there is no fractionation in these intervals. However, due to the implied slow growth rate for this type of ice, these samples most likely represent freezing that has simply intersected the meteoric water line in that interval.

Figure 18 illustrates the separation of the icing ice samples based only on depth in the ice core. Since all of the samples fall within the same scatter without any significant groupings into separate fields, there does not appear to be any significant trends in the isotopic composition with depth, which might be expected if the water source varied seasonally.

Figure 18: A co-isotopic plot separating the icing ice by depth within the stratigraphy. The LMWL for glacier B-26 is also shown.

5.4 Overall Stratigraphic Relationships

Due to the distance separating most of the boreholes it is difficult to correlate the stratigraphy between them, and therefore the overall pattern of formation of the icing will be inferred from the results of the GPR survey of 1993.

In both the Annual and Perennial portions of the icing, the overall stratigraphic pattern consists of a series of sub-horizontal layers, of variable thickness, that consistently originate at the glacier/icing contact and then follow the length of the valley as they progress downslope (Moorman, personal communication). Some layers were noted to pinch out prior to the end of the survey line, only to be overlain by subsequent layers which prograde further downslope. This style of ice growth duplicates the ice appearance noted by Schohl and Ettema (1990) in their experiments.

Within the Annual icing, some details disrupt the overall stratigraphic pattern. A continuous sub-surface tunnel, approximately 30 cm in diameter, was noted to exist at a consistent depth of 2-3 m along the full length of the GPR survey on the Annual icing (Moorman, personal communication). This feature was then penetrated by drilling to reveal an open conduit with a steady flow of water. It is uncertain whether tunnels of this nature can be formed or maintained during the formation period of the icing, however, it may be that this feature provides a conduit for the transmission of unfrozen water down the length of the valley during the colder winter months when surface flow is restricted.

Some lens-shaped ice bodies, on the order of several metres vertical thickness and tens of metres in horizontal extent, were also noted to exist in the Annual icing. Although these ice layers form a similar horizontal stratigraphy, they develop downvalley of the glacier/icing contact and terminate prior to the end of the survey line. It was suggested (Moorman, personal communication) that these occasional ice lenses may represent a lateral flow of icing source water, originating from the north margin of the icing at some position downstream. This is not uncommon in other icings noted in the literature and may simply represent flow that was constrained along the bedrock margin.

In the Perennial icing, no tunnels or lenses of ice disturb the stratigraphy as the Perennial ice appears to be more fully consolidated and consistent in its appearance. It was also noted in the GPR results (Moorman, personal communication) that the Perennial ice is not as water saturated as the Annual icing, suggesting that it is fully frozen in place. This most likely adds to the stability of the Perennial ice during the erosional summer period.

Significant deposits of clastic sediments were also noted to exist within the meandering stream channels crosscutting the Annual icing. Large quantities of sediment was also noted by W.W. Shilts (personal communication) in 1991, to be discharging onto the surface of the Perennial icing during the development of a water fountain (displaying three feet of hydraulic head above the surface of the icing) located at the glacier/icing contact. However, the icing ice itself was noted, in all boreholes and hand sections examined over the period of study, to be pristine in

nature with little or no visible clastic sediments incorporated into the ice body. Also, none of these sediments were found to be preserved within the icing ice during the geophysical survey of either the Annual or Perennial icing portions. Therefore, it is suggested that the sedimentation associated with the icing is solely an erosional feature, created by the rapid flow rates occurring in the summer months. It is possible that the sediment load forms the base upon which the newly forming icing ice is deposited once the previous years ice is removed during the summer.

5.5 Summer 1992

5.4.1 Borehole #1

Stratigraphy

In the ice stratigraphy of Figure 19, Borehole #1 displays a transitional style of icing ice growth from the bottom to the top of the section. At a depth of 4.0 m and below, the icing ice consists mainly of Candle to Bubble-Rich varieties, implying a slower overall growth rate of ice layers during this period and hence the likelihood of relatively warmer air temperatures. The top 2.0 m of the section, however, consists mainly of Bubble-Rich to Milky ice, indicating faster ice growth and therefore colder ambient air temperatures. This trend may be showing a transition towards a colder fall or winter temperature regime. It is unclear from the ice types, however, whether this transition is sharp or progressive as there are significant Snow ice intervals in the central 2.0 m of the section, which interrupt the stratigraphy and prevent direct correlation between the upper and lower portions.

Table 7 separates the ice into the four main ice types discussed previously (Candle, Milky, Bubble-Rich and Clear) that are related to icing processes (Snow ice is not shown as its characteristics are solely dependent on precipitation effects and therefore cannot be compared with the other ice types). The Table displays the average $\delta^{18}\text{O}$ value, the range of $\delta^{18}\text{O}$ composition, and the percent of the total borehole thickness represented by each ice type.

BOREHOLE #1

Figure 19: Stratigraphic section showing the variations in ice types, isotopic composition and electrical conductivity with depth for Borehole #1 (Annual Icing sampled in 1992).

Ice Type	Isotopic Mean	High Range	Low range	% of Borehole
Candle	-23.9	-23.5	-25.2	3.0
Bubble-Rich	-22.5	-23.0	-25.0	30.0
Milky	-24.0	-23.5	-24.2	3.5
Clear	-23.6	-23.2	-24.0	22.0

Table 7: The oxygen isotopic range and mean values, as well as the percentage of Borehole #1 represented by each of the four main ice types developed in the text.

Ice Type	Isotopic Mean	High Range	Low Range	% of Borehole
Candle	-23.7	-22.0	-26.0	41.0
Bubble-Rich	-22.7	-22.0	-25.2	37.9
Milky	-23.7	-23.0	-25.2	9.7
Clear	-23.0	-22.0	-24.2	8.7

Table 8: The oxygen isotopic range and mean values, as well as the percentage of Borehole #3 represented by each of the four main ice types developed in the text.

Ice Type	Isotopic Mean	High Range	Low Range	% of Borehole
Candle	-24.3	-23	-26	10
Bubble-Rich	-25.2	-21	-27	68.5
Milky	N/A	N/A	N/A	N/A
Clear	-23.3	-23	-24	3.6

Table 9: The oxygen isotopic range and mean values, as well as the percentage of Borehole #4 represented by each of the four main ice types developed in the text.

As shown, the main style of ice growth consists of Bubble-Rich and Clear ice intervals which, when combined, make up over 90 % of the icing ice, not including the snowfall layers. This is not surprising as these ice types represent the largest range of freezing temperatures, while the Milky and Candle ice varieties require specific environments in which to form.

Although not shown in the table, Snow ice does form 40 % of the total stratigraphy for the borehole, more than any other single ice type. A possible explanation for the large amount of snow accumulation at this location may be snowdrift build-up. Since it was noted that the Annual icing undergoes significant erosion during the summer melt period, while the Perennial icing remains essentially intact, the Annual portion of the icing must, therefore, form a depression in the surface of the icing body. This may preferentially serve to collect any windblown snow that falls on the icing, or on the land surface surrounding the icing, to develop the fairly extensive thicknesses of Snow ice noted in the borehole.

Electrical Conductivity

The electrical conductivity values over the length of core are typically low ($< 20 \mu\text{S/cm}$) with few exceptions (Figure 19). Only two layers of Candle ice at depths of 3.91 m ($60 \mu\text{S/cm}$) and 3.98 m ($165 \mu\text{S/cm}$) display elevated values above $30 \mu\text{S/cm}$, which is most likely a result of the trapping of expelled solutes during the slow ice growth from the top and bottom interfaces.

A similar pattern of change is manifested in the conductivities to that shown to exist in the stratigraphy. As the type of ice changes, a progressive increase in the conductivity values from the bottom of the section to the top is developed. Below a depth of 3.0 m, conductivity values are less than $5 \mu\text{S/cm}$. Between 2.2 m and 3.0 m, values are near $10 \mu\text{S/cm}$, and in the intervals above this, conductivity gradually increases to near $20 \mu\text{S/cm}$. The magnitude of the change in values is minor over the length of the section, and the amount of variation from one depth interval to the next is also quite low (generally less than $5 \mu\text{S/cm}$). Therefore, this trend in icing ice growth appears to be gradual and continuous rather than sudden, which may imply a continuity in the temperature regime, rather than an abrupt transition.

None of the thick layers of Milky ice in Borehole 1 display elevated conductivity values. This suggests that the concentration of dissolved solutes at this borehole site was quite low since a representative sample of bulk water conductivity should be trapped by this ice type.

Oxygen Isotopes

In the stable isotopes, the greatest fluctuations seen in Figure 19 occur in the Snow ice intervals where the $\delta^{18}\text{O}$ values range from -24.5% to -22% . This is not surprising as the isotopic composition of snow is dependent on the temperature of condensation during the snowfall (Dansgaard, 1964), and this can vary on a daily basis.

The average isotopic value for the section is -23.6‰ with few fluctuations from the mean. At a depth of 2.0 m, a 10 cm interval of layered Bubble-Rich Milky ice displays a more depleted value of -24.9‰ . The most likely cause of this depletion is that the central half of the interval was noted to be much clearer (10 % bubble content) than the bubble-rich layers bracketing it (40 % bubble content). The reduced bubble content in the centre of the layer implies that the freezing rate decreased over this depth, allowing fractionation to increase sufficiently to cause a depletion.

A similar level of depletion exists in a Candle ice layer formed at a depth of 3.91 m. The Candle ice, due to its slower growth rate, appears to have developed an equal level of depletion to that of the Bubble-Rich ice, even though it is much thinner. This situation illustrates an important process in icing ice development. It appears that dissimilar rates of ice growth, and variable ice layer thicknesses, can interact to produce similar isotopic results despite a difference in the appearance of the ice.

In Table 7, Bubble-Rich and Candle ice display a similar range of possible isotopic compositions from -23‰ to -25‰ , while Milky and Clear ice display a similar range from -23‰ to -24‰ . This appears to suggest that Bubble-Rich and Candle ice growth follow similar formation patterns, as do Clear and Milky style ice. However, the mean values for the ice types in the table reflect something closer to the expected freezing rate trend. Candle ice displays the most depleted average isotopic values (-24‰) followed by Clear ice intervals (-23.6‰) and then Bubble-

Resolution Test Chart Labels:

- 1.0
- 1.1
- 1.25
- 1.4
- 1.6
- 1.8
- 2.0
- 2.2
- 2.5
- 2.8
- 3.2
- 3.6
- 4.0
- 5.0

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Rich ice (- 22.5 ‰). This latter trend shows that the freezing rate does, on average, govern the isotopic composition of the ice. However, it appears that, under the right source conditions, ice layer thicknesses and environmental conditions, fractionation effects can be developed that do not follow this trend.

Co-Isotopic Relationships

The results of the investigation into the overall freezing effects at this location are shown in Figure 20, a co-isotopic plot of the selected samples from Borehole #1. The chosen samples plot along a best fit line with a slope of 6.69 and a strong regression value of 0.99. The reason for this strong relationship remains unclear as the samples consist of several ice types and come from several different depth intervals in the section. Since the slope of the regression line is 6.69 and not the predicted slope of 5.91 (see section 6.2.2) for freezing, it appears that they are not aligned due to a common freezing effect.

Figure 20: A co-isotopic plot illustrating icing ice from Borehole #1 separated by slow and fast growth rates. The Glacier B-26 LMWL is shown.

5.5.2 Section 1

Candle Development

In Section 1, a different style of ice formation is represented. Most of the ice consists of either pure Candle ice or Clear ice mixed with more bubble-rich varieties. This indicates a very slow style of ice growth over most of the section, with little of the expected variability to climate. Since the ambient conditions cannot be radically different between the two Annual sections, due to their proximity, the changes in ice build up must be due to site-specific variability.

As winter progresses, surface water flow is not likely to be able to travel long distances, as freezing will rapidly restrict the areal extent of the water. Borehole #1 is much closer to the outlet source of the glacier, so that even on extremely cold days, glacial discharge is likely to be able to flow across the surface and reach this location before completely freezing. This may explain the occurrence of the entire range of possible ice types, at Borehole #1.

In the case of Section 1, only the slow freezing varieties of ice formation are represented. This suggests one of two possibilities: the days must be consistently warm if the water moves across the surface, or the water must be consistently insulated to remain unfrozen for a reasonable period of time. The latter explanation is more plausible as it is unrealistic to expect weather conditions to remain stable throughout the period of icing formation.

Candle ice growth has been documented within some of the tunnels cross cutting the icing strata, which typically produce an angular unconformity in the icing strata as the flowing water is frozen in place within the confines of the eroding tunnel. Although these tunnels may be an adequate environment for Candle ice growth, the production of thick successions of Canded beds in one locality (as in the case of Section 1) is difficult to account for solely by growth within an aerally restricted tunnel.

As shown in Figure 21, there was nearly 3.5 m of continuous Candle ice formed at this site, separated into smaller candles varying in length between 0.5 to 1.5 cm, which end in pronounced to subdued terminations. This implies either fifty individual layers of icing ice or 2-3 m of unfrozen water undergoing pulsed, slow ice growth.

A working hypothesis is that at the upper surface of a body of unfrozen water (either at the surface of the icing or within a vacant cavity within the stratigraphy) Candle ice, of sufficient thickness to insulate the remaining water below from the harshest effects of the shifting climate, began to grow. This is tentatively supported by the fact that both the 0.3 to 1.8 metre Candle interval and the 2.2 to 3.0 metre Candle interval display a single, continuous candle of 10 cm in length at the top of the interval. After this, a succession of 0.5-1.5 cm long candles follow within the remaining ice body of both intervals. This suggests that the large, initial Candles floated on top of a preserved body of water which would periodically freeze in response to changes in the air temperature disrupting equilibrium.

Ice Stratigraphy

SECTION #1

Figure 21: Stratigraphic section showing the variations in ice types, isotopic composition and electrical conductivity with depth for Section 1 (Annual Icing sampled in 1992).

At each freezing pulse, the newly formed ice layers would reduce the thermal gradient between the cold air and the warmer water, which would most likely stop the continued formation of the ice layer. This newly established equilibrium would then continue until the ice layers above cooled over time to a temperature well below zero, which would then initiate the formation of a new candle. The length of time between freezing pulses would be quite variable, and dependent on the ambient air temperature. Small candle growth likely represents formation during cooler days since the equilibrium would be disrupted more rapidly.

At times it appears that this balance can be offset even more dramatically. Milky and Bubble-Rich intervals of up to 10 cm thickness separate some of the larger Candle bodies, indicating that temperatures probably dropped significantly below zero over a short period of time.

Candle Source Changes

A further complication is also visible in the co-isotopic plot for the section (Figure 22). The Candle ice layers analyzed for the depth intervals of 150-160 cm and 170-180 cm, plot along a slope equal to the freezing slope of 5.91 (the 160-170 cm depth interval is not included in this discussion due to unresolved analytical difficulties encountered with this sample during laboratory analysis). This indicates that they were frozen from a continuous, 30 cm thick, body of unfrozen water (if the 160-170 interval does not plot separately from those intervals which bracket it), with the same initial source water isotopic composition. However, despite the fact that the depth intervals of 120-130 cm and 130-140 cm are stratigraphically adjacent to each

Figure 22: A co-isotopic plot illustrating the icing ice samples from Section 1. The depths are shown in centimetres below surface. The Glacier B-26 LMWL is also shown.

other, all of the remaining samples in the figure plot individually along their own distinct freezing slopes with disparate initial source water compositions. This indicates that there must be a periodic flux of water into the unfrozen water body over time, leading to the development of source changes within the water body.

Several speculative explanations can be made to account for the change of water within the pool. Thermal melt by the unfrozen water could lead to a gradual downwasting of the pool deeper into the icing, eventually exposing a weaker layer of icing ice. A tunnel could then form in the less competent layer, draining the pool and forming a cavity which then would be re-filled. A similar effect could be caused by a rupture in the ice above the pool which would allow the water to escape to the surface, thereby forming a cavity which would later be re-filled. This case is similar to the formational history often displayed by frost blisters (see Chacho, 1990; Kovacs, 1992; Michel, 1986; Pollard, 1990, 1983; Pollard and French, 1983; and van Everdingen, 1978). Another way to adjust the source composition over time involves the mixing of the water in the reservoir pool without drainage in response to a new discharge at the glacial outlet with a different isotopic composition.

Whatever the cause of the source change, the co-isotopic evidence reveals that some layers are developed from a continuous, stable source. Therefore, there must be some time lag between the drainage/mixing and re-charge events that allows the site to remain as an undisturbed water pool for a length of time.

Electrical Conductivity

The specifics of the section may now be examined (Figure 21). The pure Candle ice layers of the section ranged from elevated conductivity values (typically above $50\text{--}60\ \mu\text{S/cm}$) in half the intervals to very low values ($< 10\ \mu\text{S/cm}$) in the other half. This most likely reflects the expelling of solutes during slow ice growth, and the subsequent concentration of solutes in the layers frozen below. However, a sudden change in the conductivity values may also represent a new influx of source water into the system carrying a greater or lesser concentration of dissolved material. Two examples of solute enrichment can be seen at depths of 2.6 m and 2.8 m with electrical conductivity values of $105\ \mu\text{S/cm}$ and $118\ \mu\text{S/cm}$, respectively.

In the depth intervals below 3.0 m (i.e., below the main Candle development) conductivity values similar to Borehole #1 are exhibited (i.e., $< 20\ \mu\text{S/cm}$ in general) with two exceptions. At depths of 4.0 m and 4.2 m there are 10 cm intervals each with elevated conductivity values ($110\ \mu\text{S/cm}$ and $90\ \mu\text{S/cm}$, respectively). In both instances, there is evidence of a downcooling concentration of solutes represented by clearer ice becoming more bubble-rich at the end of the interval.

Stable Isotopes

The stable isotopes of the candles reflect large variations in composition throughout the stratigraphy, with a range in $\delta^{18}\text{O}$ values from -23.5‰ to -26.0‰ . In the lower portion of the section (below 3.0 m), the stable isotopes display a range in $\delta^{18}\text{O}$ values from -23.0‰ to -24.5‰ , which is similar to the Annual ice values found in Borehole #1. This similarity in the isotopes and solute concentrations between this

portion of Section 1 and Borehole #1 may imply that, prior to the development of the water pool and candle growth, icing formation at this location could have followed a similar pattern of growth, with similar source water, to the location of Borehole #1. However, this is difficult to assess, explicitly, without co-isotopic data from this portion of Section 1.

5.5.3 Boreholes #2 and #3

Stratigraphy

Table 8 (page 79) illustrates a similar breakdown of the four main ice types (Candle, Bubble-Rich, Milky and Clear) for Borehole #3, to that provided for Borehole #1. Borehole #2 was not similarly displayed because its 0.9 m depth does not provide an adequate cross-section of the site.

Since the locations of Borehole #3 and Borehole #1 are at approximately equal distances from the glacier snout, a comparison of the processes involved in the icing build-up from the Perennial section (Borehole #3) to the Annual section (Borehole #1) can be undertaken. By comparison of the data shown in both Tables 7 and 8 it can be seen that the amount of Bubble-Rich and Milky ice developed between the two sections is roughly correlative. Added together, these ice types form 33.5 % of the strata in Borehole #1 and 46 % of the strata in Borehole #3. However, the amount of combined slow growth rate ice (Candle and Clear ice) developed between the two sections is radically different. In Borehole #1, 25 % of the strata are formed by the slow growth rate ice types, while in Borehole #3, 49.7 % of the strata consist of these ice types.

The most reasonable explanation for this disparity in the ice type percentages lies in the fact that Borehole #1 incorporates nearly 40 % Snow ice in its stratigraphy, while Borehole #3 incorporates less than 5 %. It is unclear as to whether an equivalent amount of slow growth rate ice would develop at the Borehole #1 location if the snow layers were not present.

Electrical Conductivity

The conductivity values for both boreholes #1 and #3 (see Figures 19 and 24, respectively) follow a similar trend, with the majority of the intervals, with few exceptions, being less than $40 \mu\text{S/cm}$. Once again, similar ice types to Borehole #1 concentrate solutes, as shown in the interval of Candle/Milky ice at a depth of 1.5 m in Borehole #3. Here, the interval begins with a low dissolved solute content ($15 \mu\text{S/cm}$), which becomes more enriched at the bottom of the interval ($60 \mu\text{S/cm}$), indicating the downward freezing of slow growth ice and the expulsion of solutes.

A similar level of solute concentration is seen at a depth of 4.15 m in Bubble-Rich/Milky ice. This 5 cm interval was noted to display a particularly elevated bubble content compared with the remainder of the sequence of similar ice. Either a different source of water is freezing at a similar growth rate, or a localised saturation of solutes occurred at this specific depth within the larger water body.

In Borehole #2 (see Figure 23), there are only two elevated conductivity levels in the section, a Candle ice layer located at 0.2 m depth ($50 \mu\text{S/cm}$) and a Milky ice layer directly underlying it ($105 \mu\text{S/cm}$). This Milky layer appears to be anomalous when compared with the very low background conductivities for Milky ice in both Boreholes #2 and #3 (generally near $20 \mu\text{S/cm}$).

BOREHOLE #2

Figure 23: Stratigraphic section showing the variations in ice types, isotopic composition and electrical conductivity with depth for Borehole #2 (Perennial Icing sampled in 1992).

BOREHOLE #3

Figure 24: Stratigraphic section showing the variations in ice types, isotopic composition and electrical conductivity with depth for Borehole #3 (Perennial Icing sampled in 1992).

Stable Isotopic Relationships

The stable isotope compositions of ice recovered from Borehole #3 display a greater range in δ values than those from Borehole #1. However, the majority of the values, with few exceptions, lie within 1 ‰ of the mean value for the section (-23.7 ‰) .

The mean stable isotopic values by ice type, shown in Table 8 (page 79), are nearly identical to those in Borehole #1. Both boreholes follow the same freezing rate trend in the mean values (i.e., Candle to Clear to Bubble-Rich ice, from most depleted to least), only deviating from each other by a maximum of 0.3 ‰. However, this mean is produced in the Perennial ice by a broader range of values within the various ice types. The range of $\delta^{18}\text{O}$ values in the Candle ice of Borehole #1, for example, was -23.5 to -25.2 ‰, whereas for the Perennial ice the range was -22 to -26 ‰.

If the Perennial ice was formed in one year, this broad range may reflect a greater degree of fluctuation in climate or in source water composition during icing growth in the past. However, if the Perennial ice was formed over several years of accumulation, annual changes in climate may be responsible for increasing the range of the values. It is impossible to determine which scenario is correct without direct dating methods which were not available during the course of this study.

Perennial Source Changes

Although the mean and range of the isotope composition in the Perennial ice are close to those in the Annual icing, the co-isotopic plot of the Perennial ice samples (Figure 25), suggests an entirely different initial source value. By applying the freezing slope of 5.91 to the full range of values of the selected sample intervals shown in Figure 25, the extrapolated initial source isotopic values fall into a range of composition between -25.5 and -26.5 ‰ for oxygen, and between -190 to -205 ‰ for hydrogen. The example freezing slope through the Candle ice interval at a depth of 150 - 160 cm displays an intercept at -26.5 ‰, as does the Borehole #2 sample. A freezing slope encompassing all of the remaining points (160 cm and 360 cm and 80 cm) plot at -25.5 ‰. The 300 - 310 cm depth interval will be discussed momentarily.

This range is much more depleted than the clustered value of -23 ‰ for oxygen in Borehole #1, which may mean that there are two disparate, and consistent, sources feeding the icing, one flowing along the northern margin of the glacier and discharging into the northern Annual portion, and another discharging from either the centre of the glacier (possibly from an unknown conduit feeding the fountain in the centre of the icing) or from the southern edge of the glacier.

A tentative hypothesis for the difference in the isotopic composition of the source outputs may be the existence of a flow barrier within the centre of the glacier (either physically or hydrologically controlled) such that inputs from two different locations are isolated from one another. The different source inputs may flow along

two different travel paths within the glacier, acquiring meltwater from glacier ice with varying isotopic compositions. It is possible that flow through the northern part of the glacier travels at a different depth within the glacial stratigraphy, which may possess a different isotopic signature than in the south/central conduits. However, a successful dye-tracer experiment would be required to successfully demarcate such flow paths through the glacier.

The Candle ice sample at a depth of 300 - 310 cm plots with an initial source water isotopic composition near to the Borehole #1 range of values at - 23 ‰. This may represent an anomalous source water change within the Perennial ice build up where the Annual flow path may have dominated for a time. A second possibility may be that a tunnel penetrated to this location, after Perennial ice deposition, transmitting water with an Annual isotopic signature which froze into a Candle ice interval. Both these explanations are very tentative as only one sample is being discussed.

Figure 25: A co-isotopic plot of the Perennial icing samples. Depths shown are in centimetres below surface. The LMWL for glacier B-26 is also shown, as well as an example freezing slope through the 150-160 cm depth interval.

5.5.4 Borehole #4

Conductivity and co-isotopic plotting for Borehole #4 was not carried out as the samples remained in Estonia after the oxygen isotopic analysis was completed, and further tests on the ice were not possible. In lieu of this, the oxygen isotopes and ice stratigraphy alone are used to infer the growth relationships for the borehole.

As seen in Figure 26, this borehole displays a different appearance in its stratigraphic and isotopic relationships. The most outstanding feature is that over 80 % of the strata are composed of layered Bubble-Rich/Milky ice with only occasional layers of the various other ice types. This is unusual, since only the Candle ice of Section 1 has shown a single ice type dominating the icing stratigraphy so completely.

There are also significant repetitive cycles in the oxygen isotopes. Each depth interval containing the pattern is initiated by the presence of a relatively enriched isotopic value, which then becomes more negative with depth along a progressive depletion curve, until some level of peak depletion is reached. The composition then returns to the initial level of enrichment along a similar curve. There are approximately eight of these cycles displayed in the icing stratigraphy of the borehole.

Cycle Characteristics and Formation

The cycles display several unique properties. Angular unconformities were seen to occur in conjunction with the depth intervals containing the most enriched portion of many of the isotopic cycles. Such unconformities were noted at depths of 1.45 m, 2.25 m, 2.65 m, 2.95 m, and 4.0 m. Also, green algae and clay-sized mineral inclusions were found to be contained within the ice of these cycles in nearly every

Ice Stratigraphy

Figure 26: Stratigraphic section showing the variations in ice types and electrical conductivity with depth for Borehole #4 (Perennial Icing sampled in 1992).

instance, neither of which were apparent in the ice of any other borehole. The only other locations where green algae were noted to exist during the course of the field work were in various meltwater ponds on the upper surface of the icing. These sediment inclusions further suggest direct exposure to the atmosphere as wind blown dust could not otherwise contaminate the generally pristine icing ice.

A working hypothesis is that the angular unconformities represent the intersection of the borehole with the edge slope of a channel or pool developed on the surface of the icing. If this is true, the horizontal ice bodies lying above this contact would represent the subsequent infilling and freezing of the depression by an influx of surface water.

Support for this theory can be inferred in the ubiquitous presence of Bubble-Rich to Milky ice within the stratigraphy, which hints at surface deposition. Since this ice type displays the greatest range of ice growth rates, and, therefore, can represent the greatest range of ambient air temperatures, it would most often be the ice type developed on the surface of the icing. The occasional Clear and Candle ice layers in the stratigraphy would most likely represent freezing on relatively warm days when growth rates could be reduced.

The cycles within the isotopic signature appear to support this hypothesis as well. Each of the enriched values at the lower end (i.e., deeper in the stratigraphy) of the cycle most likely represents the signature of the icing ice at the edge of the pool which forms the "container" for the subsequent influx of water. Where no unconformity is noted, the edge has probably eroded further away from the position

of the borehole and, therefore, is not represented.

The upper and lower curves defining the cycles can be seen to represent the progressive freezing of water over time from both the substrate and atmospheric contacts, with the maximum depletion being the depth of the last unfrozen water existing between the growing ice bands.

Although these ice types generally imply a rapid growth rate, the interlayered nature of the interval would allow for greater amounts of fractionation to occur in the bubble-poor portions of the ice, where freezing rates may be lowered sufficiently to establish a higher degree of fractionation.

The dearth of any other ice type in the stratigraphy may be a result of the implied erosion that must be present in this sequence. Other surface flows may indeed deposit ice of a more variable nature at the location of this borehole. However, a continual development of surface depressions implies, by definition, the removal of subsequent ice layers from the record by erosion. The formation of subsequent ice layers would also provide the excess thickness of icing ice necessary to "host" the up to one metre of depression ice that is shown to exist between some of the unconformity contacts (eg., cycle between 1.4 m and 2.25 m).

An explanation for the sequential surface ponding at this site is problematic. It may be related to the borehole's proximal location to the main cross-cutting surface stream of the icing, which is noted on the topographic maps to be perennial in nature. A meander in the flow path of the stream may lead to the development of stranded surface water ponds during the summer months which were noted at

several locations across the icing. Once the pond is established, thermal erosion will continue to expand the size and extent of the depression over time, as well as to add more water to the system, thereby speeding up the process.

During the fall months of icing build-up, ponding would form reservoir catchments for any surface or tunnel water flows which reach this downstream location. This water would subsequently freeze to form the cycles discussed above. If the reservoir is completely infilled after a single water flow, one season's growth of the depression Bubble-Rich ice may be terminated. This may represent the formation pattern of the sequences in which a cycle is followed immediately by a second unconformity and the start of a second cycle (eg., cycle interval 2.25 m to 2.65 m directly underlain by cycle interval 2.65 m to 3.0 m). This style of ice growth may result from the direct erosion of the overlying ice the following year.

If the reservoir is not completely filled by water initially, a new cycle could be developed without an unconformity as the new influx of water would be frozen on the previous horizontal interval, rather than on the sloped sides of the depression ice (eg., cycle interval 1.05 m to 1.45 m underlain by cycle 1.65 m to 2.25 m which has no unconformity at its upper portion).

It is unclear as to how many seasons pass during the erosional hiatus between two subsequent cycles. It is possible that because of the distal location of the borehole, cold years may not provide flow far enough down the icing which may, in turn, prevent the development of a cycle. Also, a lack of fresh inputs to the site would prevent the development of the "host" ice for a new depression in a given year.

Isotopic Composition

A final difference separating this borehole from those at other locations is that here the isotopic signature of the ice is more depleted on the whole than in other sections. Table 9 (page 79) illustrates the same breakdown of ice and isotopes by ice type as shown before. Although the Clear and Candle ice categories display a range similar to that for Borehole #3, the Bubble-Rich category (into which Milky was grouped for the purposes of this discussion) displays a range in oxygen isotopic composition from - 21 ‰ to - 27 ‰ and a mean value of - 25.2 ‰. Since the Bubble-Rich variety represents the main depositional type for the sequence, its much broader range and more depleted mean isotopic value are more indicative of the borehole than are the other ice types.

This greater degree of depletion may be a result of freezing during surface water flow from the source. As seen in previous co-isotopic plots, Bubble-Rich ice does display some minor freezing effects which may occur in situ or during surface water flow. Since Borehole #4 represents the only sampled interval this far from the glacier source that is still formed primarily by surface freezing, it is quite possible that this extra depletion is the normal amount for surface flow freezing effects for icing ice at this distance from the source.

5.6 Summer 1993

5.6.1 Boreholes #5 and #6

Since the data for both Boreholes #5 and #6 (see Figures 27 and 28) only display ice stratigraphy and electrical conductivity relationships, they will be discussed concurrently.

In detail, the conductivity values of Borehole #5 are typically below $50 \mu\text{S/cm}$ with the only exceptions noted in a Clear ice layer at 1.0 m depth ($80 \mu\text{S/cm}$) and a Milky ice layer located at 2.6 m depth ($60 \mu\text{S/cm}$). Borehole #6 displays values below $80 \mu\text{S/cm}$, with exceptions noted in a Bubble-Rich/Milky ice layer at 5.5 m depth ($90 \mu\text{S/cm}$), a Clear/Milky ice layer at 6.4 m depth ($120 \mu\text{S/cm}$) and in a Milky ice layer at 7.9 m depth ($130 \mu\text{S/cm}$).

The variations in the solute concentrations with depth appear to follow similar processes to those outlined in previous sections. One example is in the initial expulsion of solutes from the upper surface of a slow growth ice layer, to the subsequent trapping of solutes in the centre of the water body. Such a situation is noted in a layered Clear/Milky ice unit in Borehole #5 between the depths of 2.7 m to 2.9 m where the interval begins at $15 \mu\text{S/cm}$ and progresses to a value of $53 \mu\text{S/cm}$. Other general processes discussed above are similarly represented.

Tables 10 and 11 show the separation of Boreholes #5 and #6, respectively, into the four main ice types outlined previously, illustrating the percentage of each ice type represented over the length of core, as well as the mean electrical conductivity of each ice type.

Figure 27: Stratigraphic section showing the variations in ice types and electrical conductivity with depth for Borehole #5 (Annual Icing sampled in 1993).

Figure 28: Stratigraphic section showing the variations in ice types and electrical conductivity with depth for Borehole #6 (Annual Icing sampled in 1993).

Ice Type	Conductivity ($\mu\text{S}/\text{cm}$)	% of Borehole
Candle	30.4	13.5
Bubble-Rich	26.1	14.7
Milky	40.2	7.4
Clear	35.7	38

Table 10: The range and mean values for electrical conductivity, as well as the percentage of Borehole #5 represented by each of the four main ice types developed in the text.

Ice Type	Conductivity ($\mu\text{S}/\text{cm}$)	% of Borehole
Candle	41.8	4.4
Bubble-Rich	38.9	23.7
Milky	36.8	12.5
Clear	48.9	50

Table 11: The range and mean values for electrical conductivity, as well as the percentage of Borehole #6 represented by each of the four main ice types developed in the text.

The stratigraphy, similar to the situation noted for 1992, is dominated by the mid-range growth rates of the Clear and Bubble-Rich ice types. However, a higher percentage of Clear ice is indicated over that of Bubble-Rich ice, which is the reverse of the 1992 trends. This may suggest that 1993 displayed a warmer Fall/Winter period than 1992 which would serve to explain the preference for the slower growth rate Clear ice over the Bubble-Rich. It may also be that the timing of surface water flows more often coincided with warmer ambient air temperatures in 1993 than in 1992 which would also account for the change of style.

Although these boreholes are located in the Annual icing, there is no evidence of a progressively increasing trend in the conductivity values from the base of the core to the top as there was in Borehole #1 in 1992. This may be the result of a greater fluctuation in the climatic conditions during the icing formation period of 1993, or by a continual change in the solute content incorporated during the surface water flow. Both explanations would serve to prevent the development of a smooth progression in solute concentrations over time.

Further support for a fluctuating solute content is seen in the large range of conductivities present in the Milky ice layers within both boreholes, which was suggested earlier to trap a representative sample of the bulk water conductivity. In Borehole #5 the Milky ice layers display values ranging from $15 \mu\text{S}/\text{cm}$ to $40 \mu\text{S}/\text{cm}$, while in Borehole #6, the range is between 10 and $130 \mu\text{S}/\text{cm}$, suggesting wide variations in travel path solute acquisition. Without the aid of isotopic analyses (which could not be performed due to time limitations) it is difficult to tell if these

variations are caused either by changes in bulk water solute content at the source, or through variations in the contents of the travel path.

5.7 Origin of the Icing Source Water

There are two main possibilities that could comprise the initial source water inputs for the icing under study: glacial melt and a groundwater source. These two source water types can usually be differentiated initially by conductivity measurements as a groundwater flow regime generally incorporates more solutes than in direct glacial discharge. However, although the conductivity of the icing ice is typically very low, as evidenced in the Milky ice samples from both the Annual and Perennial samples, low conductivity values for groundwater have been demonstrated in other arctic localities (Johnson, personal communication) and this may also be the case for Bylot Island.

Isotopically, the disparate source water regimes shown to exist for the Annual and Perennial ice could represent a glacier source for one and a groundwater source for the other. However, the Milky ice samples from both Borehole #3 and Borehole #1 (which are assumed to represent bulk isotopic compositions) plot universally on the glacier ice meteoric water line. This suggests that glacier melt or lake drainage events, as outlined previously, does represent the bulk source water for both regimes rather than a disparate groundwater source. However, if the recharge area for the groundwater regime is nearby, local precipitation may also be the direct source for the groundwater flow regime as well, resulting in a similar isotopic signature to that of the glacier ice in the area. In addition, there is no evidence of an icing source in any of the fractionated samples that does not extrapolate to a position on the meteoric water line near to the regimes indicated by the Milky ice samples.

Therefore, it remains unclear, by either solute content or isotopic evidence, as to whether groundwater represents a considerable input to the icing source as background samples were not able to be taken of any visible groundwater outputs for the area, and a dye-tracer study was not able to be undertaken to define the characteristics of groundwater for the area.

Chapter 6: Summary and Conclusions

The overall stratigraphic pattern of the icing under study consists of a series of alternating clear and bubble-rich ice layers ranging in individual thickness from a few millimetres to up to half a metre. Several informal "ice types" were defined to delineate the varying appearance of the ice. This classification was based on visual estimates of bubble content and size, ice competency and ice crystallography.

Variations in ambient air temperature were shown to define the appearance of the icing ice. This climatic factor was shown to govern the freezing rate of the surface water flow which, in turn, defined the bubble content and ice crystal size of the icing ice. Rapid freezing rates were found to develop numerous millimetre-sized, spherical bubbles forming a "milky haze" within the ice. Moderate freezing rates typically developed centimetre-sized, egg-shaped or cylindrical bubbles, isolated in an otherwise clear ice body. Slow freezing rates generally resulted in clear, bubble-free ice, which may display a defined hexagonal crystal habit in some cases.

The ground penetrating radar data illustrated that some icing layers pinch out prior to reaching the end of the valley, while subsequent layers are shown to override these and travel further downstream. In addition, an internal tunnel complex was shown to exist at a depth of 2-3 m within the northern annual part of the icing. It was inferred that these tunnels may be responsible for unfrozen water reaching the far end of the valley, as they would provide an insulated environment for winter water flow, when surface flow is restricted by cold temperatures.

The stable isotope data suggest that a complex relationship exists between source water isotopic variations and a freezing effect in developing the overall isotopic signature of the icing ice. In most depth intervals, both processes operate concurrently, suggesting the need for co-isotopic analysis to fully define the isotopic character of the icing ice.

The degree of the isotopic freezing effect was shown to vary depending on the formation history of the icing ice. Rapid freezing rates appeared to preclude the development of any fractionation effects as equilibrium conditions could not be developed. Consequently, these horizons may represent the bulk isotopic composition of the source water at a given sampling location at that time.

Moderate freezing rates displayed fractionations on the order of 1-2‰ for the oxygen isotopes and 5-10‰ for the hydrogen isotopes. The only examples of extensive fractionation were found to occur during slow ice layer growth (Candle ice), especially where there was an indication of the existence of an insulated pool of unfrozen water. In these ice layers, depletions of up to 4‰ for oxygen and 20‰ for hydrogen were noted. This is most likely the result of stable, equilibrium fractionation provided by the sufficiently slow growth rate.

Electrical conductivity values were found to be low in all sections (rarely exceeding 50 $\mu\text{S}/\text{cm}$). Isolated instances of elevated solute content were seen to develop when solute expulsion from an upper and lower interface preferentially concentrated dissolved matter within the central portion of the freezing water layer. This results in a gradient of solute content within the layer, with low conductivities

bracketing an elevated value.

Very fine layering (on the millimetre-sized scale) was noted to represent a single freezing event occurring in a thicker body of water, freezing at a slow rate. In this case, bubbles and solutes are expelled before the freezing front until saturation of the water is reached. At this point, a layer of bubbles is frozen in place, aligned perpendicular to the freezing front. This produces a stratigraphy of thin bubble-rich layers (millimetre scale) alternating with thicker, bubble-poor horizons (centimetre-scale thickness), both of which may be mistaken for separate, individual layers.

Ice appearance is shown to be deceptive in delineating individual ice layer boundaries. In many instances, continuous layers of ice, with identical morphologies, have been shown to display broad fluctuations in source water isotopic compositions. This was interpreted to represent the presence of several discrete flows of surface water freezing under similar environmental conditions.

The source water for the icing is inferred to be a combination of meltwaters derived from glacier B-26, augmented by drainage (either periodic or continuous) from several ice-dammed lakes associated with the glacier. Source water most likely travels through the complex internal drainage system believed to exist in most glaciers to an outlet near the icing/glacier contact. Intermittent growth of the icing ice may be related to the opening and closing of glacial conduits, causing a necessary re-routing of the flow patterns within the glacier which may halt discharge for a time.

The fluctuations in the internal flow system of the glacier may also be responsible for variations in the source water isotopic compositions found to exist in

all boreholes within the icing. As the water moves through different portions of the glacier, it may acquire inputs from melted glacier ice of varying composition, thus altering the bulk composition of the water.

It is possible that a flow barrier exists within the glacier drainage system as icing ice along the northern portion of the valley displayed a different isotopic signature in source water than the boreholes in the central portion of the icing. This may imply separate and distinct flow paths along the north and south of the glacier, although this must remain inconclusive without a successful dye tracer experiment.

Recommendations

For future research, co-isotopic analysis of icing ice is essential for outlining the freezing history of an ice body, as a single element cannot effectively distinguish between the simultaneous effects of freezing and source water variations. Dye tracer experiments would be useful indicators in fully defining the variations and locations of the source water forming the icings.

If a perennial icing is being investigated, direct dating methods, such as tritium, could prove useful in determining the age of the icing, as well as the span of time involved in the formation of the icing (a single year or multiple years).

Geophysical surveying of the icing proved to be useful for "filling in the gaps" between direct borehole investigations. The author recommends that an extensive geophysical survey should be undertaken prior to drilling, in order to discover the best locations for borehole sites.

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APPENDIX 1
OXYGEN AND HYDROGEN ISOTOPIC DATA

Borehole Number and Depth Interval	Isotopic Composition
Borehole #1 (200-210 cm)	-186.9
Borehole #1 (390-392 cm)	-190.3
Borehole #1 (392-397 cm)	-192.0
Borehole #1 (397-400 cm)	-174.8
Borehole #1 (440-450 cm)	-179.3
Borehole #1 (460-470 cm)	-178.8
Borehole #2 (19-21 cm)	-201.0
Borehole #3 (80-90 cm)	-192.2
Borehole #3 (100-110 cm)	-181.5
Borehole #3 (150-160 cm)	-189.7
Borehole #3 (160-170 cm)	-179.7
Borehole #3 (270-280 cm)	-200.0
Borehole #3 (300-310 cm)	-181.1
Borehole #3 (415-420 cm)	-193.2
Section 1 (60-70 cm)	-181.2
Section 1 (120-130 cm)	-191.0
Section 1 (130-140 cm)	-187.3
Section 1 (150-160 cm)	-182.0
Section 1 (170-180 cm)	-195.0

δD ISOTOPIC COMPOSITION OF VARIOUS ICING ICE SELECTED SAMPLES

Depth Interval (cm)	Isotopic Composition
10	-22.6
20	-23.6
30	-23.7
40	-24.2
50	-23.5
60	-24.0
70	-23.6
80	-23.2
90	-23.6
100	-23.8
110	-22.9
120	-23.2
130	-23.7
140	-22.8
150	-23.1
160	-23.2
170	-23.4
180	-23.1
190	-23.3
200	-23.3
210	-24.9
220	-23.7
230	-23.7
233	-23.2
234	-22.8
237	-23.2
240	-23.5
250	-23.2
260	-23.1
270	-23.0
280	-22.6
290	-22.6
300	-22.9
310	-22.7
315	-22.7

BOREHOLE #1

Depth Interval (cm)	Isotopic Composition
320	-23.0
330	-22.8
340	-22.5
345	-23.1
350	-23.9
360	-23.3
370	-22.9
380	-23.1
387	-22.9
390	-23.2
392	-25.4
397	-24.8
400	-23.1
410	-23.0
420	-23.0
430	-23.1
440	-23.6
450	-23.7
460	-23.5
470	-23.7
480	-23.1
490	-23.3
500	-23.4
510	-23.6
520	-23.3
530	-23.5
540	-22.9
550	-23.2
560	-23.2
570	-23.2
580	-23.2
590	-23.1
600	-23.5
610	-23.4
620	-24.4
630	-23.1
635	-22.9

BOREHOLE #1 CONT'D.

Depth Interval (cm)	Isotopic Composition
10	-24.0
15	-22.6
19	-22.8
21	-26.4
22	-23.8
26	-23.2
30	-22.7
40	-23.4
50	-23.3
60	-23.4
70	-23.7
80	-24.0
82	-24.6
86	-22.3
90	-23.4

BOREHOLE #2

Depth Interval (cm)	Isotopic Composition
10	-23.1
20	-22.9
30	-23.5
37	-23.5
40	-22.4
42	-22.7
45	-22.3
50	-23.0
55	-22.0
60	-24.2
65	-22.8
70	-24.6
80	-24.0
90	-25.3
94	-23.7
100	-23.9

BOREHOLE #3

Depth Interval (cm)	Isotopic Composition
110	-24.0
114	-23.7
117	-22.7
120	-23.3
130	-23.8
134	-23.4
138	-24.3
140	-23.7
150	-23.4
160	-24.6
170	-23.2
180	-24.2
184	-23.2
190	-23.5
200	-24.6
210	-23.5
220	-23.1
225	-23.5
230	-23.2
240	-24.6
250	-23.5
256	-24.0
263	-23.5
270	-22.9
280	-26.0
290	-23.5
300	-23.1
310	-24.6
315	-23.3
320	-22.2
330	-23.4
340	-24.0
345	-22.9
352	-23.7
360	-24.7

BOREHOLE #3 CONT'D.

Depth Interval (cm)	Isotopic Composition
370	-21.3
380	-24.1
388	-23.1
394	-22.2
400	-23.7
405	-23.2
410	-23.9
415	-23.5
420	-25.2
426	-23.1
431	-22.9
440	-23.1
444	-22.4
448	-23.0
456	-23.2
460	-23.3
469	-23.4
475	-23.0
480	-23.4
490	-22.5
498	-24.1
504	-22.3
509	-22.9
516	-23.0

BOREHOLE #3 CONT'D.

Depth Interval (cm)	Isotopic Composition
5	-23.3
8	-23.8
11	-23.0
15	-23.7
20	-25.5
25	-23.6
30	-26.1
32	-23.6
36	-23.7
40	-24.9

BOREHOLE #4

Depth Interval (cm)	Isotopic Composition
45	-24.1
50	-24.0
58	-25.0
63	-24.5
70	-25.1
80	-25.1
85	-24.3
90	-24.1
95	-23.9
100	-25.7
105	-23.9
110	-24.4
115	-25.0
120	-25.4
124	-25.4
128	-25.6
131	-24.7
135	-25.3
140	-23.6
145	-24.0
155	-23.9
160	-24.0
166	-24.4
170	-23.9
175	-24.2
180	-24.5
190	-24.8
195	-26.4
200	-25.4
205	-26.1
210	-25.0
215	-25.2
220	-24.8
225	-24.2
230	-24.4

BOREHOLE #4 CONT'D.

Depth Interval (cm)	Isotopic Composition
236	-24.8
240	-25.0
245	-24.8
250	-26.0
255	-25.0
260	-24.7
265	-24.4
270	-23.2
280	-24.0
285	-23.6
290	-24.2
295	-24.1
300	-22.8
315	-25.3
320	-24.2
325	-24.5
330	-24.5
335	-24.4
340	-24.8
345	-25.1
350	-24.6
355	-25.0
360	-24.9
365	-24.2
370	-24.0
375	-24.0
378	-25.5
385	-24.6
390	-24.7
395	-24.4

BOKEHOLE #4 CONT'D.

Depth Interval (cm)	Isotopic Composition
405	-23.9
410	-24.6
415	-25.2
420	-26.8
425	-26.8
430	-25.0
435	-24.0
440	-23.6
445	-24.1
450	-24.2
455	-24.2
465	-25.4
470	-24.5
475	-23.5
480	-22.6
485	-23.1
490	-23.8
495	-23.6
500	-23.4
505	-23.0
512	-23.3
520	-23.1
525	-20.8
530	-22.5
535	-22.4
540	-22.5
545	-22.5

BOREHOLE #4 CONT'D.

Depth Interval (cm)	Isotopic Composition
10	-23.5
20	N/A
30	-24.3
40	N/A
50	-24.8
60	-24.6
70	-24.9
80	N/A
90	-25.1
100	N/A
110	N/A
120	N/A
130	-26.0
140	-24.8
150	N/A
160	-23.7
170	-24.2
180	-25.7
190	N/A
200	-24.9
210	-24.8
220	N/A
230	-23.7
240	-24.2
250	-23.7
260	-24.4
270	N/A
280	-24.5
290	N/A
300	-22.5
310	N/A
320	-24.3
330	-23.3
340	-23.7
350	-24.4

SECTION 1

Depth Interval (cm)	Isotopic Composition
360	-23.3
370	-24.0
380	-24.0
390	N/A
400	-23.9
410	-24.3
420	N/A
430	-24.4
440	N/A
450	-22.6
460	-23.3
470	-23.6
480	-23.8
490	-24.2
495	-23.8

SECTION 1 CONT'D.

Depth Interval (cm)	Isotopic Composition
5	-23.4
10	-24.2
15	-24.4
20	-23.9
25	-23.7
30	-26.1
35	-24.5
40	-23.3
45	-22.0
50	-26.1
55	-26.2
60	-24.6
65	-25.6
70	-28.0
75	-31.1
80	-36.8
85	-36.1
90	-32.7
95	-32.1
99	-30.9
110	-30.3
115	-27.3
120	-27.1
145	-23.9
150	-24.8
155	-26.2
160	-27.6
165	-27.7
170	-27.7
175	-26.7
180	-27.5
185	-26.2
190	-23.0
195	-23.5
200	-25.2

ACCUMULATION AREA

Depth Interval (cm)	Isotopic Composition
205	-25.9
210	-26.6
215	-29.0
220	-26.4
225	-26.5
230	-26.6
235	-27.0
240	-27.0
245	-26.9
250	-27.2
255	-28.6
260	-28.4
265	-28.0
285	-26.5
290	-26.9
295	-26.5
300	-26.1
315	-26.2
320	-25.9
325	-26.9
330	-28.3
332	-28.6
335	-30.2
340	-30.6
345	-32.7
350	-33.5
355	-29.5
360	-29.8
365	-29.8
370	-30.1
373	-29.4
375	-27.9
377	-29.7
380	-29.2
383	-29.6

ACCUMULATION AREA CONT'D.

Depth Interval (cm)	Isotopic Composition
390	-27.3
395	-26.3
400	-25.7
405	-23.6
408	-23.9
412	-25.3
420	-25.7
430	-26.2
435	-27.2
440	-29.2
445	-32.3
450	-30.3
455	-31.5
460	-34.8
465	-33.2
470	-31.1
475	-30.4
480	-32.1
485	-30.3
490	-29.5
495	-29.5
500	-27.8
505	-27.7
510	-26.7
513	-26.0
520	-27.0
522	-25.0
527	-24.9
530	-25.3
533	-25.3

ACCUMULATION AREA CONT'D.

APPENDIX 2
ELECTRICAL CONDUCTIVITY DATA

Depth Interval (cm)	Conductivity (uS/cm)
10	18.2
20	34.5
30	18.8
40	16.1
50	16.4
60	14.8
70	10.9
80	13.1
90	12.6
100	10.6
110	14.6
120	12.1
130	15.0
140	12.2
150	10.3
160	14.0
170	6.6
180	9.4
190	7.5
200	6.2
210	12.2
220	14.6
230	6.4
233	8.0
237	8.2
238	27.8
240	6.9
250	8.6
260	6.1
270	5.0
280	12.7
290	14.2
300	6.7
310	5.0

BOREHOLE #1

Depth Interval (cm)	Conductivity (uS/cm)
315	4.8
320	5.2
330	2.8
340	4.3
345	4.6
350	7.6
360	10.2
370	6.5
380	4.6
387	2.9
390	3.5
392	69.0
397	10.2
400	169.4
410	7.1
420	3.8
430	3.6
440	4.8
450	7.7
460	6.8
470	4.9
480	3.5
490	3.8
500	5.8
510	3.9
520	3.1
530	3.7
540	3.1
550	5.8
560	4.0
570	4.6
580	4.1
590	4.9

BOREHOLE #1 CONT'D.

Depth Interval (cm)	Conductivity (uS/cm)
10	14.4
20	67.3
30	16.6
40	28.6
50	6.6
60	9.3
70	58.1
80	59.2
90	14.2
100	60.1
110	32.7
120	52.3
130	53.6
140	23.2
150	45.8
160	9.0
170	58.8
180	40.2
200	18.0
210	15.2
220	41.5
230	33.6
240	37.0
250	16.1
260	8.2
270	107.8
280	4.8
290	117.1
300	46.6
310	33.6
320	10.4
330	67.8
340	35.6
350	20.0

SECTION 1

Depth Interval	Conductivity (uS/cm)
360	24.7
370	4.5
380	5.4
390	33.8
400	8.9
410	8.9
420	119.1
430	23.3
440	98.9
450	10.7
460	4.6
470	10.7
480	12.1
490	31.9
495	26.6

SECTION 1 CONT'D.

Depth Interval	Conductivity (uS/cm)
10	16.2
15	15.1
19	54.8
21	105.1
22	32.5
26	19.8
30	9.5
40	22.0
50	16.0
60	11.7
70	32.8
80	30.8
82	41.4
86	3.3
90	6.8

BOREHOLE #2

Depth Interval (cm)	Conductivity (uS/cm)
10	13.3
20	14.2
30	12.4
37	10.8
40	4.4
42	9.6
45	8.8
50	14.8
55	6.3
60	30.2
65	6.1
70	30.4
80	20.5
90	39.4
94	20.8
100	12.3
110	27.2
114	16.4
117	4.8
120	14.1
130	21.3
134	10.7
138	12.2
140	10.7
150	21.4
160	60.2
170	16.0
180	35.1
184	23.2
190	16.6

BOREHOLE #3

Depth Interval (cm)	Conductivity (uS/cm)
200	22.5
210	20.5
220	13.8
225	16.6
230	16.8
240	41.3
250	19.5
256	17.9
263	14.2
270	15.0
280	39.4
290	38.9
300	20.8
310	41.3
315	11.6
320	4.9
330	26.9
340	30.2
345	16.0
352	26.6
360	11.2
370	9.4
380	8.7
388	10.4
394	15.5
400	28.5
405	19.0
410	30.3
415	30.3
420	59.4

BOREHOLE #3 CONT'D.

Depth Interval (cm)	Conductivity (uS/cm)
426	14.8
431	16.0
440	16.8
444	12.2
448	20.6
456	19.1
460	14.2
469	16.8
475	11.7
480	17.6
490	20.1
498	24.0
504	11.6
509	3.1
516	8.9

BOREHOLE #3 CONT'D.

Depth Interval (cm)	Conductivity (uS/cm)
40	37.6
77	58.7
82	29.8
87	37.0
92	28.5
97	27.8
100	26.6
104	80.6
111	35.3
115	28.8
119	40.2
124	39.5
130	38.0
133	29.8
137	30.0
140	23.6
144	13.7
148	25.5
155	35.6
160	11.7

BOREHOLE #5

Depth Interval (cm)	Conductivity (uS/cm)
165	14.5
170	32.5
175	27.8
180	14.7
185	38.3
190	16.0
195	23.3
200	17.9
205	16.8
210	49.0
215	14.7
220	22.3
225	40.8
230	24.0
235	31.7
240	17.4
245	22.8
250	23.0
255	29.7
261	63.8
265	54.0
270	32.7
275	13.4
280	23.3
285	40.9
290	49.3
295	16.3
298	9.0
303	13.6
318	N/A
322	31.2
326	21.8
330	14.2
335	N/A
340	12.3
345	13.7

BOREHOLE #5 CONT'D.

Depth Interval (cm)	Conductivity (uS/cm)
210	N/A
213	50.3
221	N/A
226	31.3
230	43.2
235	44.5
239	60.7
246	22.5
250	37.2
254	23.3
258	50.0
262	12.0
267	48.4
427	N/A
430	23.2
434	19.9
439	11.1
443	32.9
447	44.5
451	34.2
456	20.2
461	14.6
465	14.3
472	38.3
475	28.1
478	17.9
482	34.0
486	30.8
490	36.5
492	37.8
499	35.2
503	32.7
507	52.4
511	28.9
515	12.8

BOREHOLE #6

Depth Interval (cm)	Conductivity (uS/cm)
518	39.4
524	28.5
528	24.0
531	18.1
536	30.3
541	24.5
545	43.7
549	91.8
553	40.9
557	15.6
560	24.5
565	23.5
569	11.5
571	12.4
576	10.4
581	59.2
585	13.8
588	11.5
594	10.3
599	24.6
604	7.9
607	15.6
610	59.2
615	81.6
620	47.5
624	22.7
628	16.7
633	23.7
638	24.9
643	118.5
648	30.6
653	32.3
658	58.2
663	50.8
668	25.3

BOREHOLE #6 CONT'D.

Depth Interval (cm)	Conductivity (uS/cm)
673	21.3
678	40.1
684	10.0
688	11.2
692	27.6
695	8.4
700	19.6
704	22.7
708	21.9
713	40.2
718	19.5
722	13.5
726	10.9
731	11.6
735	16.2
740	6.5
745	8.4
750	20.8
754	19.2
758	31.4
763	18.9
767	32.4
772	32.5
777	23.8
781	30.3
785	24.4
788	43.1
791	133.5
795	21.0

BOREHOLE #6 CONT'D.

APPENDIX 3
LITERATURE REVIEW

Russian Research:

Icing research in Russia has a much longer history and greater volume of studies than in North America. Alekseyev (1973) effectively divided Russian work on icings into four periods based on a similarity of focus of the research.

The first period encompasses any research carried out prior to the twentieth century. Observations of icings in this period were conducted during several major geographic expeditions to the remote regions of Russia and usually took the form of "stylistic notes" (Alekseyev, 1973) rather than rigid scientific observations. Some exceptions can be noted.

A report by Wrangel (1841) was the first to describe, in detail, the process of icing formation including: the periodic nature of the overland water flow; the freezing processes involved; and the character of the ice subsequent to formation.

Two others, Middendorf (1867) and Von Ditmar (1851) outlined many of the formation processes on river icings still in use today. Both noted the necessity for a constriction of the flow path to occur in order to generate the hydraulic pressures in the constrained channel that are necessary for the formation of the cyclic layers seen in most icings.

During the second period, between 1901 and 1920, the focus of the research became more active and scientific as icings began to create difficulties for the newly developing roads and railways in Siberia. Most of the references from this period are technical in nature, mainly from project engineers interested in relating successful experiences in combatting icing effects.

Podyakonov (1903), a mining engineer, undertook observations of river icings in Eastern Siberia and succeeded in generating a formula that related the major parameters of icing formation to one another. Although it was not a strict mathematical formula it was an effective first approximation, and marked the first attempt towards a more scientific approach to the problem of icings.

The third period, spanning from 1921 to 1950, marks the beginning of research under Soviet rule. As exploitation of Siberia's mineral wealth became more prominent, the use of road and rail during the winter months increased. This expanded contact with icings during the height of formation generated the need for more strict scientific and technical practices to be adopted in order to solve the related construction problems that were occurring

Beginning with the base theory provided by the Podyakonov formula, several researchers began to apply the relation to new case studies involving more complex and varied situations and discovered several inherent shortcomings. As a result, several modifications on the original formula were made leading to the development of a new relationship that better met with the results of the observed data.

In addition, researchers began to investigate the relationships amongst icing processes not governed by the Podyakonov formula for river icings. Tolstikhin (cited by Chekotillo, 1946) developed an idealized formula for calculating the volume of a spring fed icing based on measurements of discharge rates, aerial extent and icing thickness over time. Sumgin (1941) and Petrov (1930) undertook measurements and developed formulae on the hydraulic pressures generated in icing mound structures

and successfully extrapolated their results to the formation of ground icings. In response to the number of new observations and theories being developed, Chekotillo (1940) collected all existing material on icings up to that time in the first overview of Russian work.

The last period defined by Alekseyev was from 1951 to 1962. This period was the most productive, in Russian history, in terms of research. More than one and a half times the number of reports were published in this period than in all the history on the subject up to this time. However, by taking note of a second summary of existing work carried out by Chekotillo in 1965, very few significant advances were made in the understanding of icings during this time. Most of the work centred on icing regime, location, extent and exploitation rather than on the experimentation or data-gathering necessary to determine relevant processes.

From this time period to the present, research in Russia has focused on the massive perennial icings of Siberia which are studied as indicators of large and dependable sources of groundwater. The research style during this period continued to be focused mostly on icing extent, distribution and stability rather than on origin and processes.

In the volume by Alekseyev on Siberian Naleds, Bondarev and Gorbunov (1973) attempted to make some statements on icing formation processes and to classify icings according to those formation histories. Also in this work, Chistotinova and Tolstikhin (1973) measured the hydrochemistry of several large icings in Yakutia and inferred the effect of varying chemistry on icing development and extent.

Tolstikhin and Tolstikhin (1974) presented a concise summary of icing formation, structure, chemistry, morphology, growth and regime.

The Proceedings of the Second International Conference on Permafrost, Yakutsk, (1973) contained several papers (Chernyavskya; Osokin; Pisarkiy; Savko; Sokolov; and Tsvid;) on icings, which again focused on regime, distribution and size rather than processes. The absence of any icing references in the Russian literature from the late 1970s to the present may represent a lack of continued research effort on this subject in the east.

North American Research:

There are no North American references to icings prior to 1900 despite the extensive exploration of Alaska and the Yukon before this time. It is unclear how much effect prior Russian work had on early research in the west (Carey, 1973).

The first North American reference to icings was published in 1904 by a GSC researcher named Tyrell who referred to "layered sheets of clear ice lying on the alluvium of the Yukon tundra" (Tyrell, 1904). Calling them crystophenes, he associated their origin with the development of massive ground ice being "wedged" between deposits of alluvium. This has since proven to be an erroneous assumption.

In the early part of the twentieth century, several geographic expeditions to Alaska (Henshaw, 1909; and Leffingwell, 1919; Prindle, 1909) made reference to large-scale river icings discovered in the mountain valleys at higher latitudes. Leffingwell made reference to previous work by Middendorf (1867) when attempting to make statements as to the unclear origin of river icings, suggesting that some

awareness of the Russian experience did exist with regard to these features.

Several reports in the 1930's on the geology and mineral resources of Alaska, undertaken by the United States Geological Survey, made general references to icings. In particular, a U.S.G.S. Bulletin by Smith and Mertie (1930) provided a fairly detailed account of icings on the Killik River in Alaska, mentioning icing extent, thickness and stratigraphy (Carey, 1973).

The construction of the Alaska highway and railroad system led to the publication of the first papers on the effect of icings on construction and on early techniques to alleviate the difficulties (Carey, 1973). Most notable were papers by Sterling (1935) and Taylor (1939) in which several engineering case studies were discussed.

A report on river icings in Montana (Stevens, 1940) settled a long-standing debate as to whether icings could form in areas outside of permafrost, and provided the first detailed account of icing formation from inception to decay in the western world (Carey, 1973).

With the onset of World War II, the study of icings in North America increased dramatically. As military transportation had to be maintained year round on all arctic roads (Alaska Highway, Canol Road, Glenn Highway, Richardson Highway and the Mackenzie Highway), the observation and impact of icings during maximum extent became more commonplace. Several reports (Clark, 1943; Flint, 1944; Haberle, 1943; Horner, 1944; McKeever, 1943; Richardson 1943, 1944; Spindler, 1943; Taber, 1943 and Williams, 1943) made primarily by military engineers,

dealt with the problems and solutions of icings as related to construction, and served to increase the observational database.

The most comprehensive study on icings during this time was undertaken by Eager and Pryor (1945) who made detailed observations on icings and outlined a set of twelve conditions which would lead to the formation of icings. They were also the first to discuss the effect of construction on the flow regime as another possible factor which might increase icing development.

A book on permafrost by Muller (1947) summarized the majority of Russian work on the subject and outlined a detailed methodology on how to undertake a geographic survey of icings. In addition, a comprehensive discussion on icings published by Straub and Johnson (1949) outlined many of the icing processes known up to that time.

During the 1950s and 60s, work on icings focused on engineering and technical aspects. This emphasis served to expand further the observational database on icings and the effectiveness of alleviation techniques being developed for controlling destructive icing effects.

A series of technical manuals published by the U.S. Army Corps of Engineers (several dates, all in Carey, 1973) outlined specific steps to reduce the negative effects of icings on road and building construction. Several reports (Love, 1954; Jess, 1954; Lovell, 1953; and Young, 1951) by civil engineers external to the U.S. army served to contribute modestly to the understanding of icings as well.

Some scientific papers were published during this time. Hopkins and Karlstrom (1955) of the U.S.G.S. published a study on the possible uses of icings as groundwater indicators, incorporating previous Russian thoughts on the topic.

A bibliography on groundwater in permafrost published by Williams (1964) served to collect and summarize all the available information on icings up to the end of the 1950's from both Russian and North American researchers. Thompson (1963), Lewis (1962) and Savage (1964) published papers on the icings of Alaska and the N.W.T., summarizing much of the North American research understanding up to that time.

Icing research in the early 1970s was dominated by the works of Carey (1970, 1973) and the collection of papers in the Banff Symposium on Snow and Ice (1972), which resulted in the publication of several case studies on icings. Most notable was a paper by Kane and Slaughter on the hydraulics of river icings. In the mid 1970s, work on the trans-Alaska pipeline sponsored icing observations in previously inaccessible regions of the north as shown in the work of Sloan and Zenone (1976) and Church (1974) who discussed the effects of icings on pipeline construction. Van Everdingen, in a 1974 report, summarized all existing Canadian work extant on the subject of icings, while Veillette and Thomas (1979) and Harden (1977) described the stratigraphy and morphology of some icings in the Keewatin and Alaska, respectively. At the end of the 1970s, Grey and Mackay (1979) published a comprehensive report on icings, again summarizing all existing knowledge including new work completed since the time of Carey's last report.

During the 1980s, the Fourth Canadian Conference on Permafrost produced several excellent papers (Akerman, 1982; Froelich and Slupik, 1982; Slaughter, 1982; and Van Everdingen, 1982) related to the study of icings on a wide variety of topics. Papers by Kane (1981) and Scholl and Ettema (1986) have been written on the physical mechanics of icing growth. Work by Baranowski (1987) and Hambrey (1984) has been published on observations of the Spitsbergen icings, and Slaughter (1984) has published on the effects of icing development on stream hydrology. A book on river and lake ice by Ashton (1986) includes a full chapter on icing formation.

In the 1990s, a book on the growth and decay of ice by Lock (1990) also contains a chapter on icing development and degradation. An article on the two dimensional growth of an icing by Scholl and Ettema (1990) provides an excellent insight into how an icing thickens and progrades. The Proceedings from a symposium on Northern Hydrology published in 1990 contained papers by Chacho and Pollard on the icing mounds (a related feature) in Alaska and Axel Heiberg Island. Lauriol (1991), presented observations on the chemical and isotopic content of source waters involved in the formation of icings in the Yukon. In 1992, a Cold Regions Research Laboratory (CRREL) special report (Kovacs, 1992) dealt with icing blister observations on glaciers and rivers in Antarctica.

END

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FIN

Depth Interval (cm)	Conductivity (uS/cm)
165	14.5
170	32.5
175	27.8
180	14.7
185	38.3
190	16.0
195	23.3
200	17.9
205	16.8
210	49.0
215	14.7
220	22.3
225	40.8
230	24.0
235	31.7
240	17.4
245	22.8
250	23.0
255	29.7
261	63.8
265	54.0
270	32.7
275	13.4
280	23.3
285	40.9
290	49.3
295	16.3
298	9.0
303	13.6
318	N/A
322	31.2
326	21.8
330	14.2
335	N/A
340	12.3
345	13.7

BOREHOLE #5 CONT'D.