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STABLE-ISOTOPE ($^{18}O/^{16}O$) TRACING OF FRESH, BRACKISH, AND SEA ICE IN MULTI-YEAR LAND-FAST SEA ICE, ELLESMERE ISLAND, CANADA

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ABSTRACT. Ice salinity and $^{18}O/^{16}O$ ratios were measured on 12 ice cores drilled from thick, multi-year land-fast sea ice (MLSI) off the north coast of Ellesmere Island, Canada. Fresh, brackish, and sea ice were identified in the ice cores using the $^{18}O/^{16}O$ ratios. Two cases are considered: case 1, which assumes that no isotopic fractionation occurs on freezing; and, case 2, which assumes that a maximum isotopic fractionation factor (α) of 1.003 applies. The amount of each ice type is variable among the cores, but overall the 12 cores comprise 29.6% brackish ice, 70.0% sea ice, and 0.4% fresh ice in case 1, and 42.3% brackish ice, 57.3% sea ice, and 0.4% fresh ice in case 2. The data suggest that time-dependent brackish sea-water stratification below the ice is quite common and is often associated with the inverted bottom topography. However, the stratification is not always confined to small, areally limited under-ice melt pools in inverted depressions, and neither is it a summer-only phenomenon. Brackish ice growth apparently occurs in a brackish water layer that in some instances underlies the ice sheet year-round. For both case 1 and case 2 the salinity distribution in brackish ice is positively skewed, with 50% of salinity values occurring in the range 0–0.49‰. Sea-ice salinity values are more evenly distributed. In case 1, brackish ice has mean salinity and mean $\delta^{18}O$ values of 0.66 and −19.9‰, respectively, compared to mean values of 1.88 and −6.5‰ for the sea ice. In case 2, brackish ice has mean salinity and mean $\delta^{18}O$ values of 0.75 and −18.1‰ compared to mean values of 2.03 and −5.2‰ for the sea ice. The salinity of brackish ice and sea ice, ice-growth mechanisms, and the inclusion of brine in the sub-structure are discussed briefly.

1. INTRODUCTION

There is an extensive literature on the application of stable isotopes to glaciological studies, particularly for terrestrial ice, but there have been relatively few applications of stable isotopes to marine ice studies (sea ice, ice shelves). The few published studies include: the identification of the origins of ice in ice shelves (Lyons and others, 1971; Gow and Epstein, 1972; Morgan, 1972; Grootes and Stuiver, 1986; Jeffries and others, 1988b); the oxygen-isotope content of sea ice in the Gulf of St. Lawrence (Tan and Fraser, 1976); the $\delta^{18}O$ values of frazil ice in Weddell Sea pack ice (Gow and others, 1987); and, the identification of annual growth layers in pack-ice floes (Friedman and others, 1961) and in multi-year land-fast sea ice (Jeffries and Krouse, 1988).

Multi-year land-fast sea ice (MLSI) is a common feature off the north coast of Ellesmere Island (Fig. 1). It is similar perhaps to the "sikussak" of north Greenland fiords (Wadhams, 1981), and sea ice at the Koettlitz Glacier tongue, Antarctica (Gow and others, 1965). The MSLI of northern Ellesmere Island grows in place for many years, frequently replacing ice shelf lost by ice-island calvings, and often attaining undeformed thicknesses of as much as 10 m (Jeffries and Serson, 1986; Jeffries and others, 1988a). The MSLI has a characteristic undulating surface topography of long, linear hummocks and depressions, with an average hummock spacing of about 60 m (Jeffries and Serson, 1986). On the basis of ice-thickness measurements, it has been suggested that the surface topography is mirrored by an inverted, undulating topography at the bottom side of the ice (Jeffries and others, 1988a).

Prior to 1984, there had been only a few studies of the properties of this thick, multi-year sea ice, including: some crystallographic investigations of the Markham Bay Re-entrant, formerly attached to the front of east Ward Hunt Ice Shelf (Ragle and others, 1964); an ice-thickness and growth study of Nansen Ice Plug (Fig. 1) (Serson, 1972); and, the structure of the thick sea-ice floe that supported the Soviet drifting station SP-6 (Cherepanov, 1966). It has been suggested that SP-6 calved from the thick sea ice off the north coast of Ellesmere Island, perhaps even from Nansen Sound (Serson, 1972; Walker and Wadhams, 1979).

Since 1984, we have drilled a number of ice cores in MLSI as part of a program of Arctic ice-shelf and ice-island studies. Ice-core analysis has included salinity, oxygen-isotope ($\delta^{18}O$), and tritium measurements. On the basis of the relationship between the salinity and the ^{18}O content of the coastal waters of northern Ellesmere Island, ice $\delta^{18}O$ and tritium values were used to show that: (1) the MLSI has grown from water with salinities varying from as little as 3.2‰ to as much as 31.8‰, a salinity range that includes brackish water as well as sea-water; (2) water salinity varies seasonally; and (3) snow melt is the principal source of fresh melt water being contributed to the water–ice system (Jeffries and Krouse, 1988). MLSI probably includes some brackish ice, but the amount of brackish ice and its properties have not been determined.

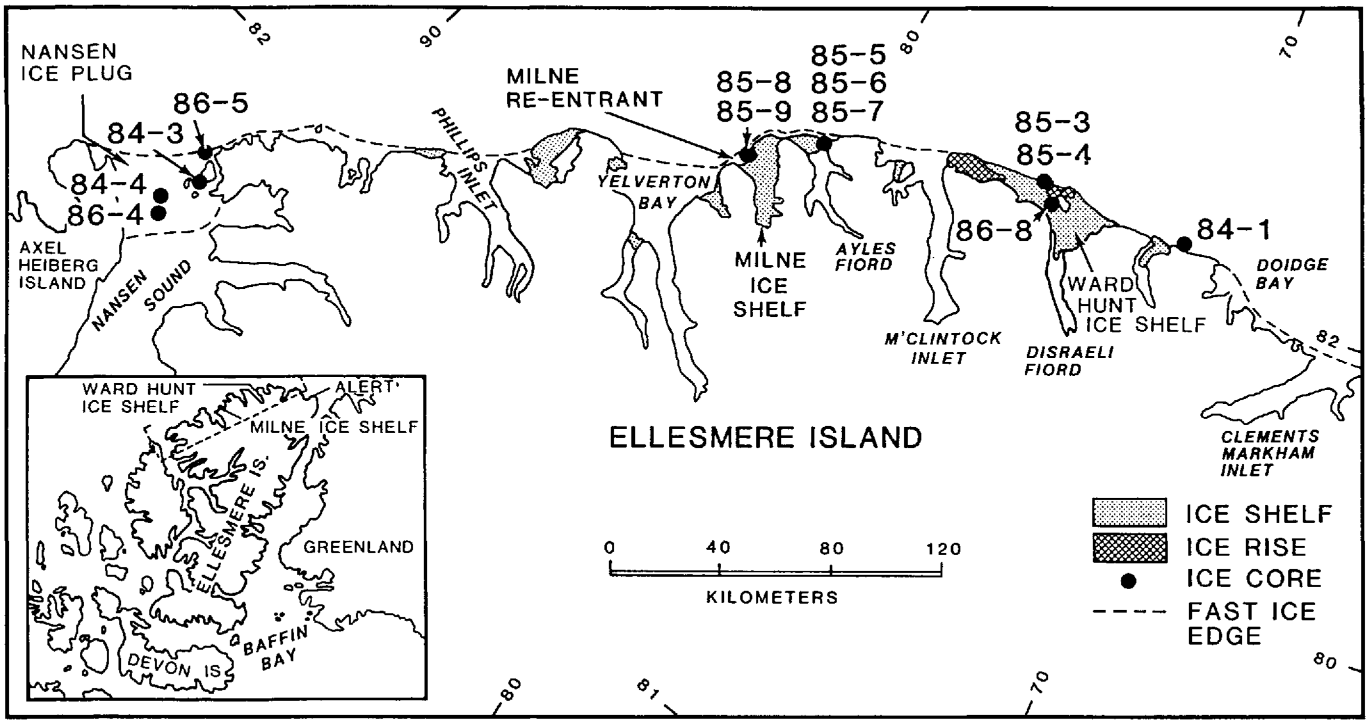

Fig. 1. Location map of ice cores drilled in MLSI, northern Ellesmere Island. Ice core 86-8 (Ward Hunt Ice Shelf) was drilled in an area where brackish ice was found by Lyons and others (1971). Data for 86-8 have been presented elsewhere (Jeffries and others, 1988b).

Significantly, brackish ice has been identified previously in Ward Hunt Ice Shelf (Fig. 1) on the basis of ^{18}O, salinity, and crystallographic analysis (Lyons and others, 1971).

There have been few studies of brackish ice and much remains to be learned of its physical and structural properties. This paper emphasizes the physical properties of brackish and sea ice in MLSI, and presents the results of δ^{18}O and salinity measurements on 12 ice cores (a total of 70.12 m of ice) drilled at locations shown in Figure 1. All cores were obtained in April or May when air temperatures were low enough to minimize brine drainage. In some cases, the cores were drilled in recognizable hummocks and depressions but, because of the snow-covered, low relative relief, it was not always possible to identify the topographic location. The emphasis of the data analysis and discussion is on the use of δ^{18}O measurements to identify brackish and sea ice in MLSI, to show the amount of each ice type present and the implications for sub-ice water properties and structure, and to examine the differences between brackish and sea-ice salinity. The field and laboratory methods have been described by Jeffries and others (1988a).

2. OXYGEN-18: A CONSERVATIVE TRACER FOR MLSI STUDIES

The recognition of fresh, brackish, and sea ice in the MLSI cores relies not on structural or salinity analysis of the ice but on the use of stable isotopes as conservative tracers of the water from which the ice grew. In this section the rationale behind this approach to ice-type identification in a fast-ice zone, where the salinity–δ^{18}O relationship for the coastal waters is well established, is explained. There are three stages in this approach.

First, it is necessary to define the salinity of fresh, brackish, and sea-water. The U.S. Navy *Glossary of oceanographic terms* (1966) defines the salinity of brackish water as 0.5–17.0‰. This definition of brackish water salinity is adopted for this study, although from the glaciologist's point of view it does not take into account the structural changes that occur as ice freezes from progressively less saline water. However, since there is as yet no diagnostic brackish ice structure, as there is for sea ice (cf. Weeks and Ackley, 1982), the identification of brackish ice according to the salinity and oxygen-isotopic composition of the brackish water from which it grew is an appropriate technique. The fresh-water, brackish water, and sea-water salinities are summarized in Table I.

TABLE I. FRESH, BRACKISH, AND SEA ICE/WATER CLASSIFICATION ACCORDING TO WATER SALINITY AND δ^{18}O VALUES, AND ICE δ^{18}O VALUES

Ice/water type	*Water salinity*	*Water $\delta^{18}O$**	*Ice $\delta^{18}O$†*
	‰	‰	‰
Sea	≥17.01	≥−15.0	≥−12.0
Brackish	0.5–17.0	−29.1– −15.1	−26.1– −12.1
Fresh	≤0.49	≤−29.2	≤−26.2

*Case 1, where no isotopic fractionation occurs and the ice δ^{18}O value is the same as the water δ^{18}O value.
†Case 2, where a maximum isotopic fractionation (α = 1.003) occurs.

Secondly, corresponding δ^{18}O values must be known for the salinity values of the fresh, brackish, and sea-water categories. For this it is necessary to know the salinity–δ^{18}O relationship in the parent water. In Disraeli Fiord and Milne Fiord (Fig. 1), salinity and δ^{18}O are related by (Jeffries, unpublished)

$$\delta^{18}\mathrm{O} = 0.85\,\mathrm{salinity} - 29.5‰. \qquad (1)$$

Using this relationship, the water salinity values (Table I) can be translated into water δ^{18}O values (Table I). The use of Equation (1) for this purpose assumes that the δ–S relationship applies to the entire study area, and that the primary fresh-water diluent of the sea-water is run-off from the land. This will be discussed further in section 4.

The third stage relates the ice δ^{18}O values to water δ^{18}O values to identify fresh, brackish, and sea ice. To do this requires that isotopic fractionation on freezing be taken into account. However, as pointed out by Jouzel and

Souchez (1982) and Souchez and Jouzel (1984), the amount of isotopic fractionation that occurs during natural processes cannot be known; under natural conditions the problem is complicated by non-equilibrium processes, the inclusion of liquid by the ice, the input and output of water to and from the reservoir, variations in freezing rates, and whether freezing occurs in an open or closed system. In the case of congelation-ice growth, it is reasonable to expect open-system conditions and near-maximum isotopic fractionation. On the other hand, this will be offset by the inclusion of brine in the ice. The inclusion of brine will be particularly critical in a mesh of congealing frazil- or platelet-ice crystals, and in this more closed system the resulting isotopic fractionation might be much less than the maximum. In view of the complex freezing processes that probably occur during MLSI growth, including congelation and frazil/platelet growth, the two extreme cases of isotopic fractionation are considered in this study, and between them they probably account for the majority of the measured δ^{18}O values in MLSI. Case 1 assumes no isotopic fractionation, so ice δ^{18}O values represent water values; case 2 assumes a maximum isotopic fractionation ($\alpha = 1.003$; O'Neil, 1968), thus, after subtracting 3‰ from a given ice δ^{18}O value, the δ value of the parent water is obtained (Table I).

Assuming that the oxygen-isotope content remains unchanged after ice formation, the isotopic fractionation is small compared to the brine loss from sea ice as it thickens and ages, i.e. the ^{18}O/^{16}O ratios of the ice are conservative tracers of the parent water. Some alteration of original δ^{18}O values might occur by infiltration and refreezing of melt water at the ice surface. Although Jeffries and Krouse (1988) suggested that melt-water infiltration at the surface of MLSI is minimal, for the purpose of this study, δ^{18}O values from the uppermost 0.5 m of ice are excluded to allow for possible infiltration of ^{18}O-depleted melt water and alteration of the original δ^{18}O value, and to exclude refrozen melt water from surface melt pools. On this basis, it is now possible to identify fresh, brackish, and sea ice directly from the ice δ^{18}O values. It is stressed that this methodology applies only to the multi-year land-fast sea ice of northern Ellesmere Island, where the δ–salinity relationship of the coastal waters is known. The methodology is "region specific" and cannot be applied to other fast-ice zones, or to multi-year pack-ice floes. Before the results of the analysis are presented, the ^{18}O content of sea-water and sea ice will be briefly discussed.

On a global basis, sea-water has a mean δ^{18}O value of about 0.0‰ (Craig, 1961), with some negative deviations arising from local input of meteoric water (meteoric water is water that has been involved in recent atmospheric circulation and has δ^{18}O values less than zero). Unlike sea-water, the ^{18}O content of meteoric water shows a latitude effect, with precipitation δ^{18}O values decreasing (becoming more negative) towards high latitudes (Dansgaard and others, 1973). In the Arctic Ocean, where meteoric water δ^{18}O values are very negative, the surface sea-water has a δ^{18}O range of −4.5‰ to +0.3‰ (Vetshteyn and others, 1974; Östlund and Hut, 1984), due to mixing of meteoric water and sea-water. Assuming maximum isotopic fractionation on freezing, the aforementioned values correspond to ice δ^{18}O values of −1.5‰ to +3.3‰. Similar values are found in MLSI, but, as will be shown, a greater proportion of the δ^{18}O values in MLSI are much more negative.

3. RESULTS OF OXYGEN-ISOTOPE AND SALINITY MEASUREMENTS

The salinity and isotope data for each core are summarized in Table II. In the combined data set of the 12 MLSI cores, salinity values range from as little as 0.01‰ to as much as 12.06‰. The wide salinity range is matched by a wide range of δ^{18}O values, from a minimum of −29.9‰ to a maximum of +0.7‰. The wide range of δ^{18}O values, and the mean values that fall in the brackish ice/water category, indicate a substantial meteoric water input to the water–ice system, and the potential for MLSI growth by the freezing of fresh, brackish, and sea-water.

3.1. **Amounts of fresh, brackish, and sea ice in MLSI**

Case 1. Assuming no isotopic fractionation, the amount of fresh, brackish, and sea ice in each MLSI core is shown

TABLE II. DATA FOR ICE THICKNESS, ICE SALINITY, AND ICE δ^{18}O VALUES

Ice core	*Length*[*]	*Salinity range*	*Mean salinity*[‡]	δ^{18}*O range*	*Mean* δ^{18}*O*[‡]
	m	‰	‰	‰	‰
84-1	3.77[†](H)	0.01 to 2.09	0.85 ± 0.41 (50)	−23.8 to −2.9	−14.0 ± 6.8 (26)
84-3	2.24	0.01 to 1.93	0.37 ± 0.33 (24)	−16.4 to −9.6	−12.9 ± 1.8 (21)
84-4	3.75	0.16 to 2.49	0.74 ± 0.46 (56)	−10.9 to +0.7	−3.9 ± 3.3 (30)
85-3	7.62 (D)	0.18 to 4.39	1.26 ± 0.45 (72)	−24.5 to −0.7	−10.9 ± 8.3 (40)
85-4	10.00 (H)	0.03 to 12.06	2.92 ± 1.54 (96)	−20.7 to −1.4	−5.2 ± 4.3 (55)
85-5	4.22 (D)	0.01 to 0.22	0.08 ± 0.06 (36)	−22.4 to −13.8	−18.2 ± 2.9 (26)
85-6	6.63 (H)	0.01 to 3.84	0.60 ± 0.58 (60)	−22.9 to −1.4	−15.2 ± 7.7 (33)
85-7	6.26 (D)	0.01 to 3.53	1.21 ± 0.73 (53)	−29.9 to −1.6	−17.3 ± 6.3 (32)
85-8	9.80 (H)	0.03 to 4.54	1.61 ± 0.97 (93)	−22.7 to −2.8	−9.5 ± 5.6 (45)
85-9	7.24 (D)	0.03 to 3.30	1.07 ± 0.73 (68)	−22.0 to −6.3	−13.8 ± 5.1 (30)
86-4	5.53	0.16 to 2.49	0.74 ± 0.46 (50)	−11.0 to +0.2	−2.9 ± 3.2 (20)
86-5	3.06 (D)	0.22 to 8.87	1.50 ± 1.52 (27)	−19.0 to −2.7	−9.6 ± 4.5 (15)

[*] The core length also corresponds to the ice thickness.
[†] H and D denote hummock and depression, respectively.
[‡] Mean values are expressed with ±1 standard deviation. Figures in parentheses are the number of analyses for each parameter for each core.

in Figure 2a. MLSI has an overall composition of 29.6% brackish ice, 70% sea ice, and 0.4% fresh ice.

Case 2. Assuming maximum isotopic fractionation, the amount of fresh, brackish, and sea ice in each MLSI core is shown in Figure 2b. MLSI has an overall composition of 42.3% brackish ice, 57.3% sea ice, and 0.4% fresh ice.

Whether one considers cases 1 or 2, clearly, brackish ice is quite common, but there is some variation in the amount of each ice type from location to location, and at a given location. Some particular features common to cases 1 and 2 are listed below:

(1) Sea ice is particularly common in the cores drilled in and near Nansen Ice Plug (Figs 1 and 2), and brackish ice is particularly common at Ayles Fiord (Figs 1 and 2), where a single fresh-ice specimen (core 85-7; Fig. 2) was also found. Contrasting salinity and $\delta^{18}O$ profiles for sea-ice core 86-4 (Nansen Ice Plug) and for brackish core 85-5 (Ayles Fiord) are shown in Figure 3.

(2) Where ice cores have been drilled in adjacent hummocks and depressions, the depression cores contain a greater proportion of brackish ice, e.g. cores 85-3 and 85-4 (Fig. 4), 85-5 and 85-6, 85-8 and 85-9 (Fig. 2). Depression ice also has a lower ^{18}O content and salinity than hummock ice (Table II).

(3) In some cores there are pronounced brackish and sea-ice strata, e.g. cores 85-3 and 85-4 (Fig. 4). The hummock core, 85-4, has two basic strata: a sea-ice layer from the surface to 7.80 m, and a sea-brackish ice layer from 7.80 m to the bottom side. The depression core, 85-3, has three

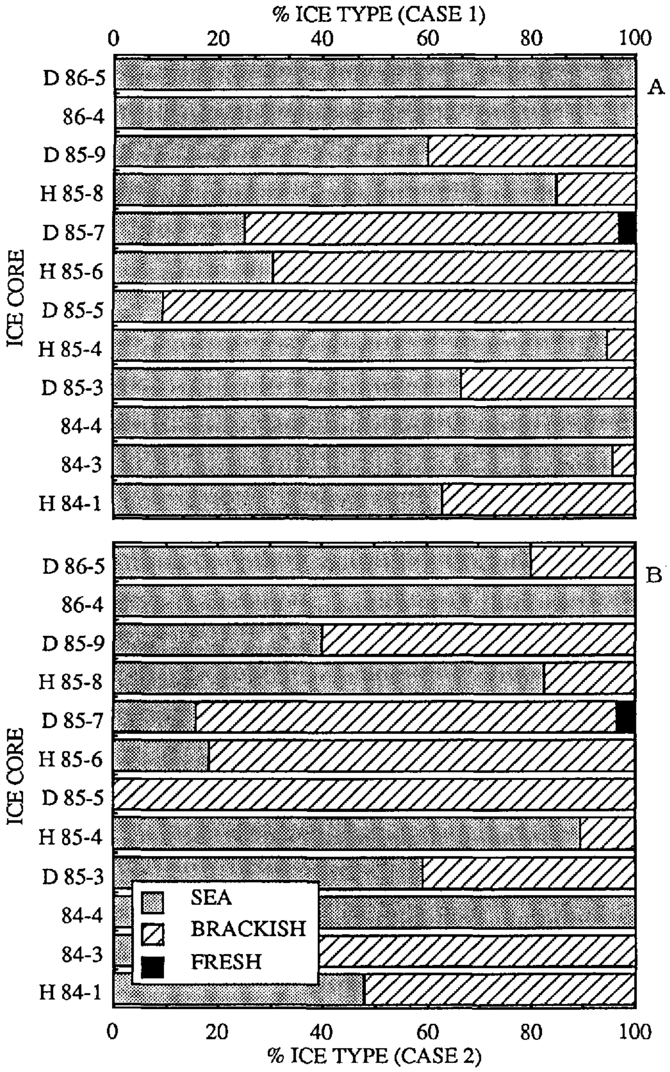

Fig. 2. Amounts of fresh, brackish, and sea ice in MLSI according to the ^{18}O content of the ice: case 1 (a), case 2(b). The ice-core identification numbers include H and D for hummock and depression locations, respectively.

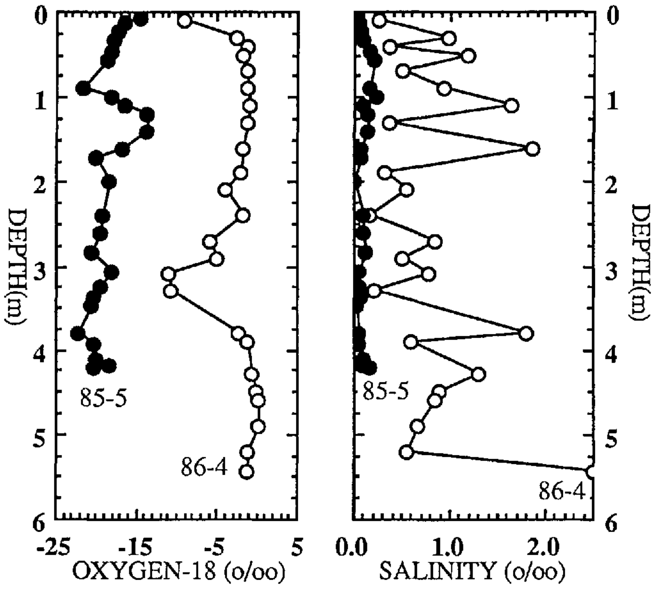

Fig. 3. $\delta^{18}O$ (left) and salinity (right) profiles in ice cores 86-4 (Nansen Ice Plug) and 85-5 (Ayles Fiord). Ice core 85-5 is a brackish core and is considerably less saline and has a lower ^{18}O content than sea-ice core 86-4. Each core shows a salinity increase at the bottom due to winter ice growth.

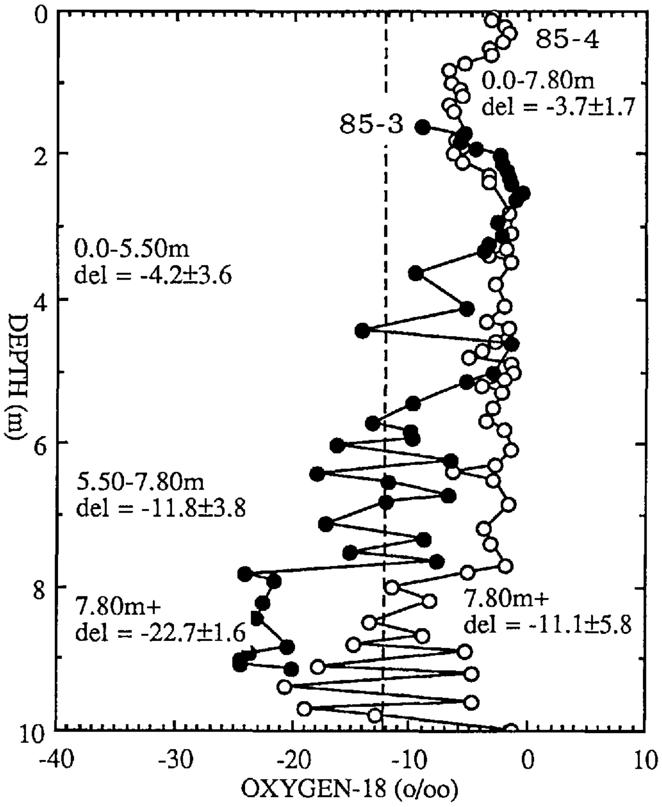

Fig. 4. $\delta^{18}O$ profiles in adjacent hummock (85-4) and depression (85-3) ice cores, deformed MLSI at the front of Ward Hunt Ice Shelf. The profiles are plotted to allow for the relative surface relief, so that hummock and depression data are at equivalent depths. These profiles assume a case 2 situation, i.e. maximum isotopic fractionation occurred during freezing. Mean $\delta^{18}O$ values for individual layers in each core are shown at the left (85-3) and at the right (85-4). The vertical dashed line separates the sea and brackish ice.

basic strata: a sea-ice layer from the surface to 5.50 m, a sea-brackish ice layer from 5.50 to 7.80 m, and a brackish ice layer from 7.80 m to the bottom side. The sea-brackish ice layers in the central section of core 85-3 and the lower part of core 85-4 consist of thin, interfingering layers of sea and brackish ice.

3.2. The ^{18}O content and salinity of brackish and sea ice

The fresh ice identified on the basis of ice ^{18}O content (δ^{18}O, −29.9‰) was found at a depth of 1.78 m in ice core 85-7. This ice was, therefore, some distance below the surface and the ^{18}O content was unlikely to have been affected by surface processes. Since fresh ice constitutes only a small proportion of the ice cores, it will not be considered further in any detail. The mean δ^{18}O and mean salinity values of sea and brackish ice, calculated on the basis of no isotopic fractionation (case 1) and maximum isotopic fractionation (case 2), are summarized in Table III. In both cases there is an order-of-magnitude difference between the mean δ^{18}O and mean salinity values of each ice type.

TABLE III. SALINITY AND δ^{18}O DATA FOR BRACKISH AND SEA ICE

	Mean $\delta^{18}O$ ‰	*Mean salinity* ‰	*Number of measurements*
		Case 1	
Brackish ice	−19.9 ± 1.9 (1 S.D.)	0.66 ± 0.53	111
Sea ice	−6.5 ±3.1	1.88 ± 1.35	264
		Case 2	
Brackish ice	−18.1 ± 2.8	0.75 ± 0.56	153
Sea ice	−5.2 ± 2.6	2.03 ± 1.46	222

On the basis of brackish and sea-ice identification according to δ^{18}O values, the distribution of salinity values for each ice type has been determined (Fig. 5). For both case 1 (Fig. 5a) and case 2 (Fig. 5b), the distribution of brackish ice salinity values has a pronounced positive skew, with 50% of values occurring in the modal class (0–0.49‰). There is a tail of higher salinity values of as much as 4‰ in brackish ice. Sea-ice salinity values are less skewed and more widely distributed, with a tail of high salinity values exceeding 4.0‰. In both brackish and sea ice, the high salinity values in the tails of the distributions are nearly all associated with the most recent ice growth at the bottom of the cores. The data (Table III; Fig. 5) show that there are two quite different salinity and δ^{18}O populations for brackish and sea ice.

4. DISCUSSION

4.1. The δ^{18}O–salinity relationship in the coastal waters

Because the amount of isotopic fractionation occurring when MLSI grows is unknown, the extreme cases were selected; one with no isotopic fractionation and one with maximum isotopic fractionation. The isotope data show that, in either case, MLSI contains a significant amount of brackish ice, and that this ice has a quite different salinity than the sea ice. These findings are based, in part, on the use of a water δ^{18}O–salinity relationship (Equation (1), section 2) for which there are two assumptions: (1) it applies to the entire study area; and (2) the primary fresh-water diluent of the sea-water in this area is run-off from the land. The first assumption is reasonable, since Equation (1) applies to Disraeli Fiord and Milne Fiord individually. Each fiord has its own catchment area, hence it is likely that run-off δ^{18}O values are quite uniform across the numerous drainage systems in the study area; an observation supported by the quite uniform mean δ^{18}O values of snow-pack at sea-level in the same area (Jeffries and Krouse, 1987).

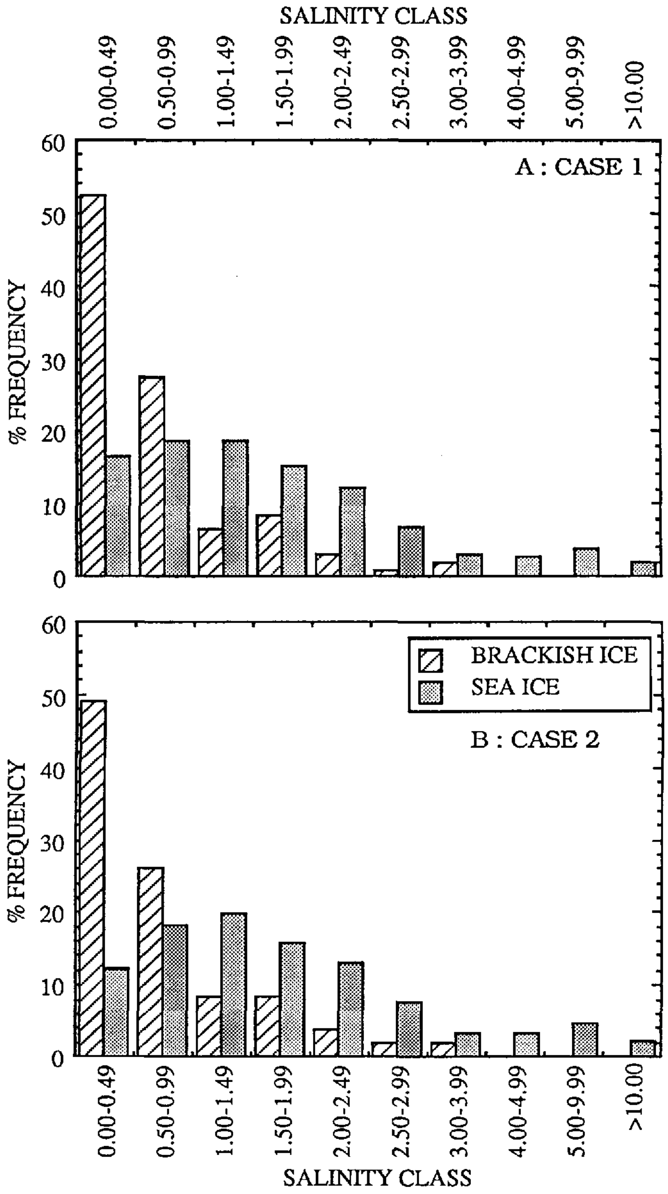

Fig. 5. Salinity distributions in brackish ice and sea ice. a. Case 1, no isotopic fractionation. b. Case 2, maximum isotopic fractionation.

Implicit in the second assumption is the exclusion of sea ice/MLSI melt water as a likely fresh-water source and diluent of sea-water. Melting of multi-year ice contributes significant amounts of "fresh" water, with sea-ice δ^{18}O values (i.e. close to SMOW), to sea-water in much of the Arctic Ocean and adjacent waters (e.g. Tan and Strain, 1980). However, in the northern Ellesmere Island coastal zone, the total area of MLSI is much less than the total area of the land-drainage systems, and the contribution of "fresh" MLSI melt water will be small compared to the amount of land run-off. The primacy of land run-off is illustrated by the year-round presence of deep layers of low-salinity water in many fiords and inlets, e.g. a 44 m deep layer of fresh water originating from land run-off is found along the entire surface length (30 km) of Disraeli Fiord (Keys, 1978; Jeffries, unpublished). Also, if sea-ice melt water, with low salinity and high δ^{18}O values, was a major "fresh-water" component below MLSI, the sea-ice salinity distribution (Fig. 5) would probably also be positively skewed. But this is not the case; hence the sharp contrast between the sea and brackish ice salinity distributions. Thus, there is considerable justification for the use of Equation (1) in the present analysis.

4.2. Brackish water and sea-water under MLSI

The ^{18}O content of the MLSI cores indicates that low-salinity or brackish water is common below MLSI. Layers of low-salinity water floating upon a sea-water layer and under a sea-ice sheet, or an ice shelf, have been described previously, and it has been common to refer to the low-salinity water layers as "melt pools" (Untersteiner and Badgley, 1958; Gow and others, 1965; Hanson, 1965; Martin and Kauffman, 1974). In the case of MLSI, the term melt pool is, in some instances, somewhat misleading as it suggests an areally limited brackish sea-water stratification confined to the inverted depressions at the bottom side. It is apparent that this is not the case, since brackish ice occurs in hummocks as well as in depressions, i.e. brackish water underlies the entire MLSI sheet at some locations and times.

Brackish sea-water stratification under the entire ice sheet is most likely to occur in the summer, when land run-off is at a maximum. Once run-off ceases or is minimized in the autumn, the stratification will become less pronounced and perhaps even dissipate. This seasonality of water properties and structure gives rise to seasonal or annual layers in MLSI (Jeffries and Krouse, 1988) and pack-ice floes (Friedman and others, 1961). On the basis of annual-layer counting in the ice cores from Milne Re-entrant (Fig. 1), it has been estimated that the undeformed MLSI was 20 years old in 1985 (Jeffries and Krouse, 1988). The longevity and immobility of the MLSI provide a stable environment for the growth of annual ice layers associated with the seasonally variable sub-ice oceanography.

The seasonality of water properties is not always a brackish water and sea-water alternation. It is apparent that MLSI can be underlain year-round by brackish water, with varying ^{18}O content and salinity, but giving rise to 100% brackish ice, e.g. ice core 85-5 (Fig. 3). The year-round persistence of brackish water is further substantiated by the water that entered the ice-core 85-5 bore hole; it had a δ^{18}O value of −24.7‰, and was sampled in early May before the onset of melting and run-off. The year-round presence of low-salinity water interposed between ice and sea-water has also been observed near the front of the Koettlitz Glacier tongue, Antarctica (Gow and others, 1965).

Under-ice, brackish water melt pools are common in inverted depressions and apparently persist year-round in those at some locations; this would account for the greater amount of brackish ice that is found in depressions compared to adjacent hummocks, and the lower mean salinity of depression ice. At other locations, however, the MLSI is apparently underlain by sea-water for most of the time, viz. the Nansen Ice Plug cores (e.g. core 86-4; Fig. 3). Water that entered the 86-4 bore hole had a δ^{18}O value of −2.7‰ and a salinity of 29.0‰, i.e. sea-water. The greater proportion of sea ice in Nansen Ice Plug than elsewhere is probably a reflection of the greater mixing of fresh water and sea-water below the ice, due to Nansen Sound being a through channel with a greater sea-water flux.

The stratigraphy of ice cores 85-3 and 85-4 (Fig. 4) is an interesting case and illustrates well the spatial and temporal variations in ice-growth history and water properties below the ice. The stratification can be interpreted in terms of three basic stages in the evolution of the ice cover in relation to the water below the ice (Fig. 6). It is evident from the surface topography of rough, hummocky, weathered ridges of the MLSI at the front of Ward Hunt Ice Shelf that the ice was once deformed (Jeffries and others, 1988a). Stage 1 (Fig. 6), represented by the ice from the surface to 3.55 m, was the deformation of a relatively thin sea-ice sheet that grew from sea-water with high (more positive) δ^{18}O values. Stage 2 was a period of brackish sea-water stratification below the depression, while the hummock remained underlain by sea-water; hence, the contrast in ice δ^{18}O values in the depth interval 5.50–7.80 m (Fig. 4). The brackish sea-water stratification was confined to the inverted depression at the bottom side, but it is apparent from the interfingering of sea and brackish ice in the central section of core 85-3 that there were regular fluctuations in the water salinity, from sea-water to high-salinity brackish water. During stage 3, brackish sea-water stratification was more extensive; low-salinity brackish water only occurred in the inverted depression, while high-salinity brackish water–sea-water stratification occurred at regular intervals below the hummock, similar to stage 2 below the depression. The most likely explanation for the interfingering of thin sea and brackish ice layers in each core is ice growth associated with the seasonal variability of water salinity and structure below the ice, i.e. annual layering in the ice. At the multi-year scale, stage 3 probably represents a 5–6 year period of greater fresh-water penetration below the ice, perhaps due to warmer summers, and/or less mixing of fresh water and sea-water, than occurred during the 5–6 year period of stage 2. The δ^{18}O record in ice cores 85-3 and 85-4 indicates that, once deformation has occurred and the ice has consolidated, the deformed MLSI also provides a stable environment for under-ice water stratification and associated ice growth.

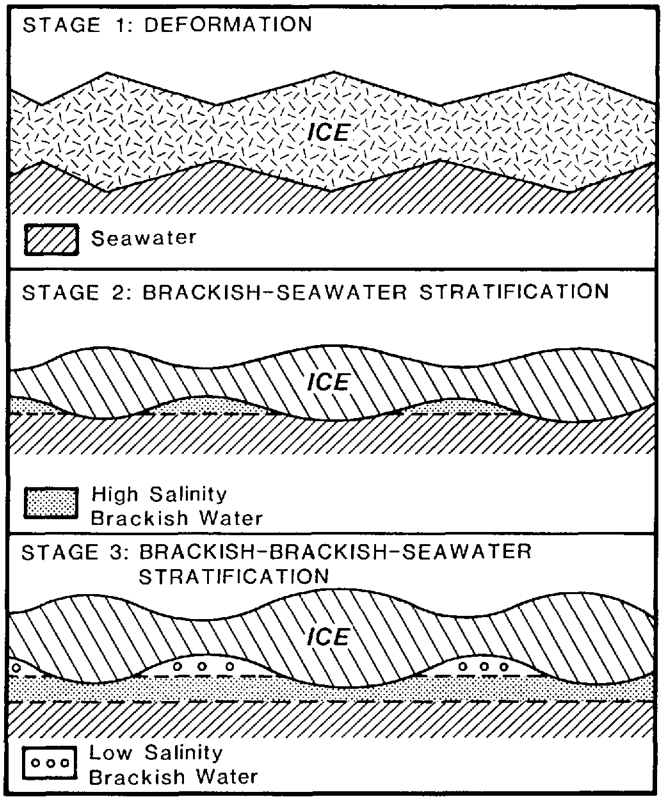

Fig. 6. Three stages in the evolution of MLSI at the front of Ward Hunt Ice Shelf interpreted from ice-core (85-3, 85-4) δ^{18}O values as a proxy record of under-ice water stratification. Stages 2 and 3 represent summer conditions.

4.3. Growth and salinity of sea and brackish ice in MLSI

Field observations and studies of the ice-growth process in under-ice melt pools suggest ice growth and accumulation commonly occurs as a mesh of loosely packed ice crystals fills the low-salinity water layer (Untersteiner and Badgley, 1958; Hanson, 1965). Understandably, these are summer observations and, since water stratification is most pronounced in summer below MLSI, the accumulation and congealing of frazil and/or platelet ice crystals is the most likely summer ice-growth process there. At those locations where water stratification persists year-round, e.g. Ayles Fiord, it might also be a winter process. Additionally, in winter there will almost certainly be congelation ice growth.

Congelation ice growth is the most common Arctic sea-ice growth mechanism, and brine inclusion in the ice occurs at a dendritic ice–water interface, with a resultant sub-structure of platelets and evenly spaced brine cells (cf. Weeks and Ackley, 1982). The sub-structure of congelation brackish ice is not well documented and it remains to be determined at which water salinities the freezing interface changes from dendritic to cellular, and from cellular to planar. From available evidence, frazil/platelet brackish ice appears not to have a sea-ice-like sub-structure; neither in "summer" ice in multi-year ice floes (Schwarzacher, 1959) nor in brackish ice in Ward Hunt Ice Shelf (Lyons and others, 1971) was a platelet sub-structure observed. Schwarzacher (1959) also found that "summer" ice salinity was considerably less than that of the ice above and below it, an observation analogous to the different salinity distributions for sea and brackish ice in MLSI. For the moment, the salinity difference between brackish and sea ice in MLSI remains an intriguing observation. It can only be suggested that the explanation for this difference probably lies with the water salinity at the time of ice growth, the resultant ice–water interface morphology and ice sub-structure, and whether ice growth occurs by congelation or by frazil/platelet mechanisms.

5. SUMMARY AND CONCLUSION

This study has shown that the δ^{18}O values in ice cores drilled in multi-year land-fast sea ice can be used to identify fresh, brackish, and sea ice, provided the salinity–^{18}O relationship in the coastal waters is known. Using this approach, it has been shown that MLSI on the north coast of Ellesmere Island, Canada, contains a significant amount of brackish ice, and that brackish ice and sea ice have quite different salinity and δ^{18}O populations. The brackish ice growth probably arises from the extensive brackish sea-water stratification that must exist beneath the ice, frequently in the summer and, in some cases, year-round. The maintenance of the under-ice water stratification and, therefore, the growth of brackish ice can be attributed to the stability of the fast ice which remains in place for many years and causes little disturbance of the water below the ice during that time. A further factor in the growth of brackish ice is the likely presence of an inverted topography at the bottom side which will tend to trap brackish water year-round in depressions.

Measurements and observations of brackish ice in the field and laboratory remain few. Further study is required before a satisfactory explanation for the salinity difference between brackish and sea ice is obtained. The MLSI in this region is a natural laboratory for the study of brackish ice that has grown by congelation and frazil/platelet mechanisms from water of variable salinity. Additional studies are needed and should include structural–crystallographic analysis in order to provide some insight into the questions of crystal structure and sub-structure, ice-growth processes and the inclusion of brine into the ice, and perhaps also how much of the low-salinity ice is contributed by melting and refreezing of the MLSI itself.

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