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SHORT NOTES

STABLE ISOTOPE ANALYSIS OF A SUBMARINE ICE CLIFF AT EXPLORERS COVE, McMURDO SOUND, ANTARCTICA

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Abstract. Stable isotope ratios and salinities of ice samples obtained from a submarine ice cliff at Explorers Cove demonstrate that the upper parts of the ice cliff have frozen directly from sea-water and are an underwater expression of permafrost, whereas the lower parts appear to be partially glacial in origin. These results indicate that there may be ice cores in the moraines of Explorers Cove, in which case the coastline of McMurdo Sound is more extensively ice-cored than previously known.

Résumé. *Analyse des isotopes stables d'une falaise de glace sous-marine à Explorers Cove, McMurdo Sound, Antarctique.* Les rapports des teneurs en isotopes stables et des salinités de la glace prélevée sur une falaise de glace sous-marine à Explorers Cove, montre que la partie supérieure de la falaise de glace a gelé directement à partir de l'eau de mer et constitue une réplique sous-marine du permafrost, tandis que la partie inférieure semble être partiellement d'origine glaciaire. Ces résultats indiquent qu'il peut y avoir des coeurs de glace dans les moraines d'Explorers Cove; dans ce cas la côte de McMurdo Sound apparaît plus largement englacée qu'on ne le pensait jusqu'ici.

Zusammenfassung. *Analyse stabiler Isotope eines unterseeischen Eiskliffs bei Explorers Cove, McMurdo Sound, Antarktika.* Die Verhältnisse stabiler Isotope und der Salzgehalt von Eisproben, entnommen einem unterseeischen Eiskliff bei Explorers Cove, zeigen, dass die oberen Teile des Eiskliffs direkt aus Meerwasser gefroren und somit eine Ausbildung von Permafrost unter Wasser sind, während die unteren Teile teilweise glazialer Herkunft zu sein scheinen. Diese Ergebnisse deuten darauf hin, dass in den Moränen von Explorers Cove Eiskerne stecken; in diesem Fall gäbe es an der Küste des McMurdo Sound weit mehr Eiskerne als bisher angenommen.

INTRODUCTION

During the 1981-82 field season, eight submarine ice cliffs were discovered along the western side of McMurdo Sound (Fig. 1). Some of these features were quite large (greater than 300 m long and in excess of 30 m tall). A description of their locations, profiles and dimensions has already been published (Stockton, 1983). Three of the ice cliffs (Miers Valley, Cape Chocolate, and Strand Moraines) were obviously the exposed faces of ice cores in adjacent moraines or glaciers intruding into the Sound. The existence of ice cores in the moraines bordering the southern parts of the west side of McMurdo Sound has been known since the early explorations (David and Priestley, 1914; Taylor, 1914, 1922; Debenham, 1921; Healy, 1975). The presence of the ice cliffs at Explorers Cove is more difficult to account for, because ice cores have not been reported on the Sound north of Blue Glacier (Fig. 1), except for a small piece of ice buried in a beach at Marble Point (Nichols, 1961).

Two uniquely different mechanisms may explain the presence of the ice cliffs at Explorers Cove. These ice cliffs may be composed of glacial ice, implying the existence of previously undescribed ice cores in the adjacent coastal moraines. Alternatively, the ice cliffs in question could have frozen directly from sea-water. It should be possible to distinguish between these two hypotheses through stable isotopic analyses of the ice cliff, because glacial ice which is formed from atmospheric precipitation is depleted in deuterium and ^{18}O relative to ice frozen directly from sea-water (e.g. Gow and Epstein, 1972; Morgan, 1972).

In this paper, we present the results of a stable isotope analysis of cores taken from an ice cliff in Explorers Cove. The data provide a basis for determining the mechanism of formation of this particular cliff and possibly of the other cliffs in Explorers Cove and elsewhere (e.g. the southern boundary of New Harbour) that are not associated with identified ice cores in moraines or with glaciers (Stockton, 1983).

LOCALITY DESCRIPTION

Explorers Cove is at the mouth of Taylor Dry Valley (Fig. 1). The mean annual surface temperature at Explorers Cove is approximately -25°C (Weyant, 1967). The shoreline is composed entirely of glacial moraine. Four ice cliffs have been located in the cove. The ice cliff which was selected for coring is approximately 70 m wide and 6 m tall (Stockton, 1983). It is located on the south side of the cove at approximately lat. 76°33'48"S., long. 163°29'17"E. This cliff was selected because it was the most easily accessible of the four in the cove.

MATERIALS AND METHODS

Ice cores were taken from the cliff and the overlying sea ice with a SIPRE corer on 8 January 1982. Two vertical cores were taken, both 40 cm shoreward from the face of the cliff and 2 m apart, midway along the length of the cliff. The first core was taken to sample the cliff systematically and the second in an attempt to get deep samples. Segments of the first core were retained at approximately every meter from both the sea ice and the ice cliff (Fig. 2). (There was a gap of approximately 50 cm between the sea ice and the ice cliff.) Segments deeper than 305 cm into the ice cliff could not be recovered for technical reasons. Attempts to recover parts of an hypothesized ice core from the moraine in the vicinity of the ice cliff (Fig. 2) proved unsuccessful because it was not possible to drill to any significant depth (greater than 0.5 m) through the moraine due to the abrasive properties of the permafrost-immobilized sediments.

In order to obtain a sample of known glacial origin, a part of the ice core in the moraine at Cape Chocolate (Fig. 1) was exposed by digging (the ice core is buried under about 20 cm of sediment). Pieces were then broken out with a shovel.

The core segments and pieces of the Cape Chocolate ice core were stored frozen, wrapped in aluminum foil.

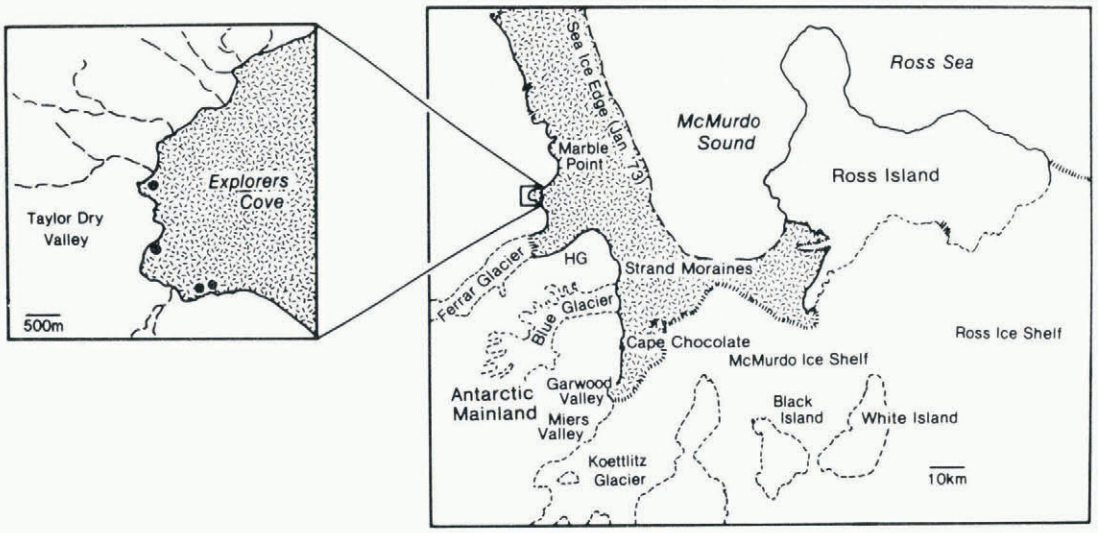

Fig. 1. McMurdo Sound and vicinity (HG, Herbertson Glacier). The shoreline from the flank of Koettlitz Glacier to Blue Glacier is ice-cored. The solid circles in the inset mark the positions of ice cliffs in Explorers Cove. Map after U.S. Geological Survey: McMurdo Sound, Antarctica (ST 57-60[152°E-180°E]). Map of Explorers Cove after U.S. Geological Survey: Lake Fryxell, Antarctica (S7730 E16300/0.25X).*

The segments were melted in beakers which were tightly covered with aluminum foil. Melting took place at approximately 20°C and was accomplished in 4-6 h. After melting, the water samples were stored in Nalgene LPE^{R} bottles and shipped back to the United States for analysis.

The hydrogen- and oxygen-isotope ratios of the water samples were determined by standard techniques (Bigeleisen and others, 1952; Epstein and Mayeda, 1953). The isotope ratios are reported in the δ notation, where

$$\delta D = \frac{(D/H)_{sample}}{(D/H)_{standard}} - 1 \times 1000\ ^{o}/oo,$$

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \times 1000\ ^{o}/oo.$$

The standard in both cases is Standard Mean Ocean Water (SMOW).

The salinities of the water melted from the samples were determined with an induction salinometer.

RESULTS

The results of the hydrogen- and oxygen-isotope ratio determinations and the salinity measurements are given in Table I. The isotope ratios determined

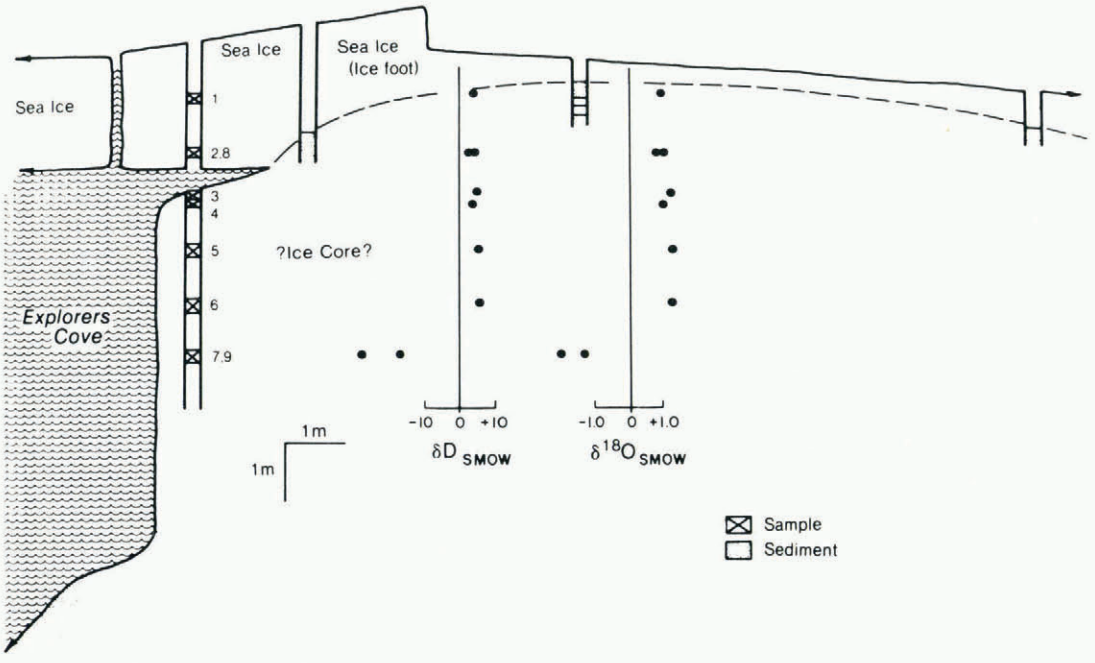

Fig. 2. A cross-section of the submarine ice cliff located at lat. 76°33'48"S., long. 163°29'17"E. The δD and $\delta^{18}O$ values of water melted from different sections of two cores that penetrated the cliff are also shown.

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TABLE I. HYDROGEN- AND OXYGEN-ISOTOPE RATIOS AND SALINITIES OF WATER MELTED FROM TWO CORES PASSING THROUGH SEA ICE AND AN ICE CLIFF AT EXPLORERS COVE (lat. 75°33'48"S., long. 163°29'17"E.), AND FROM THE MORAINE ICE CORE AT CAPE CHOCOLATE (SEE FIG. 2). THE ISOTOPE RATIOS FOR TWO STANDARDS ARE ALSO GIVEN

Number	*Sample identity*	δD_{SMOW} ‰	$\delta^{18}O_{SMOW}$ ‰	*Salinity* ‰
1	Core 1, 90-100 cm, sea ice	+4	+1.1	1.995
2	Core 1, 190-200 cm, sea ice	+4	+1.1	1.489
3	Core 1, 0-15 cm, ice cliff	+5	+1.3	1.470
4	Core 1, 15-33 cm, ice cliff	+4	+1.1	2.207
5	Core 1, 90-115 cm, ice cliff	+5	+1.3	1.610
6	Core 1, 190-215 cm, ice cliff	+6	+1.3	2.019
7	Core 1, 290-300 cm, ice cliff	-29	-3.1	1.604
8	Core 2, 190-200 cm, sea ice	+3	+0.9	2.167
9	Core 2, 290-305 cm, ice cliff	-18	-2.0	2.038
	Cape Chocolate, glacial ice	-82	-10.0	0.094
	SMOW, standard water	+1	0.0	-
	SLAP, standard water	-430	-54.7	-

for two international water standards, SLAP (accepted δD and $\delta^{18}O$ values of -428 ‰ and -54.5 ‰) and SMOW (δD and $\delta^{18}O$ values 0 ‰ and 0.0 ‰), are also given in Table I. The δD and $\delta^{18}O$ values of the samples obtained from the ice cliff at Explorers Cove are plotted against the vertical profile of the core in Figure 2.

The isotope ratios and salinities of the upper parts of the ice cliff are essentially identical to those of the overlying sea ice. The deepest cliff segments, at 290-300 cm in the first core and at 290-305 cm in the second core, have δD and $\delta^{18}O$ values lower than those of the sea ice. The salinities of these two samples are not significantly different from those of the other samples in the cliff or from those of the sea-ice samples. The sample of glacial ice from Cape Chocolate has more negative δD and $\delta^{18}O$ values and lower salinity than any of the samples from the sea ice or ice cliff at Explorers Cove.

DISCUSSION

With respect to the alternative hypotheses of glacial or sea-water origin for the ice cliff, the analysis of the samples suggests that the upper parts of the ice-cliff face were frozen directly from sea-water. The four ice-cliff samples down to 215 cm into the cliff had a mean δD value of +5 ± 1 ‰, a mean $\delta^{18}O$ value of +1.2 ± 0.1 ‰, and a mean salinity of 1.826 ± 0.344 ‰. These values are consistent with the values we obtained for the sea-ice samples and with the values that have been obtained for other ice samples frozen directly from sea-water (Gow and Epstein, 1972; Morgan, 1972). Thus, it would appear that these parts of the ice cliff are not evidence of ice cores in the adjacent moraine but are simply expressions of submarine permafrost.

The two deepest samples (290-305 cm depth) of the ice cliff have significantly lower δD and $\delta^{18}O$ values than the upper ice-cliff samples and the sea ice. The mean δD value is -24 ‰ and the mean $\delta^{18}O$ value is -2.6 ‰. These values are less negative than those we found for the glacial ice from the moraine at Cape Chocolate (Table I) and published values for other glacial ice samples, such as Koettlitz Glacier, which has δD and $\delta^{18}O$ values of about -270 ‰ and -36 ‰ (Gow and Epstein, 1972), and Taylor Glacier, which has $\delta^{18}O$ values ranging from -34.0 to -44.2 ‰ (Stuiver and others, 1981). Stuiver and others (1981) published $\delta^{18}O$ values for a number of glaciers and ice cores in moraines around McMurdo Sound. The moraine values are of particular interest here. The $\delta^{18}O$ values of samples from the west side of the Sound vary considerably, with some close to those of sea ice (e.g. Garwood Valley with values of +1.4 and +3.9 ‰), while others are highly variable and/or clearly not ice derived from sea-water, such as Blue Glacier (ranging from -41.3 to +2.3 ‰), Hobbs Glacier (-28.0 to -1.1 ‰), and Miers Glacier (-31.6 to -27.9 ‰). The precise location relative to the coastline of these samples is not known but these data serve to illustrate that the values for the deepest parts of the ice cliff at Explorers Cove are within the range covered by other moraine ice cores in McMurdo Sound. It would be interesting to know whether or not the less negative $\delta^{18}O$ values observed by Stuiver and others (1981) were for samples taken from coastal moraine ice cores and the more negative values from moraines adjacent to glaciers.

The more negative δD and $\delta^{18}O$ values we observed for the deepest sections of the ice cliff may be caused by the mixing of large amounts of ice frozen directly from sea-water (with δD and $\delta^{18}O$ values of about +5 ‰ and +1 ‰ and salinities of about 2 ‰) with small amounts of glacial ice, with more negative δD and $\delta^{18}O$ values (possibly less than -300 ‰ and -40 ‰, respectively), and with salinities less than 0.05 ‰ (Gow and Epstein, 1972; Morgan, 1972; Stuiver and others, 1981). Mixing could have occurred due to the fortuitous orientation of the core segments at an interface between glacial ice and ice frozen directly from sea-water, or might have resulted from processes such as solid-state diffusion or partial melting followed by refreezing. Our data do not permit us to distinguish among these possibilities.

The simplest interpretation of the results presented here is that the upper parts of the ice-cliff face were frozen directly from sea-water while the deepest parts of the cliff probably include remnants of glacial ice. Whether or not the upper parts of the ice-cliff face is a veneer of sea ice or a much larger piece of glacial ice is presently not known, nor is there any information available to test this possibility. Attempts to investigate the shoreward extent of the ice cliff were unsuccessful. There may be an extensive ice core behind the face of the cliff, since circular and irregularly shaped, steep-sided ponds were observed in the intertidal flats behind two of the ice cliffs. These ponds are suggestive of subsurface melting of an ice mass in the moraine (paper in preparation by DeLaca and Stockton).

Although the analysis presented here applies directly to a single ice cliff in Explorers Cove, it is possible that all of the ice cliffs in the cove and

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possibly that near Herbertson Glacier (Fig. 1) share similar characteristics and origins.

CONCLUSIONS

Stable isotope ratios and salinities of water samples obtained from two cores demonstrate that the upper seaward parts of a submarine ice cliff in Explorers Cove have frozen directly from sea-water due to the underwater effects of permafrost. The origins of the lower parts of the ice-cliff face are more difficult to interpret but appear to be partially glacial in origin, suggesting that there may be ice cores in the shore moraines of Explorers Cove. If the shoreline contains ice cores, the coastline of McMurdo Sound is more extensively ice-cored than previously known.

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