

Chemical characteristics and origin of clear basal ice facies in dry-based glaciers, South Victoria Land, Antarctica

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Abstract

This paper describes a reconnaissance investigation of the solute chemistry of a clear basal ice facies that previous studies have suggested is the product of accretion of proglacial lake water. Clear basal ice, adjacent englacial ice, lake surface ice and lake water were sampled at six locations in the Taylor and Wright valleys. Ice from each sample location was split into five aliquots and the concentrations of sodium, potassium, calcium, magnesium and chlorides were determined using atomic absorption spectrophotometry. The clear basal ice samples can be divided into three groups on the basis of solute concentrations. Group 1 consists of six samples which have solute concentrations very similar to englacial ice, Group 2 consists of seven samples that have concentrations that are significantly greater than englacial ice and Group 3 consists of one sample which has a solute concentration that is 10 times greater than adjacent englacial ice. Four mechanisms to explain the solute enrichment are examined and it is concluded that although the chemical analysis suggests that some basal ice may have been accreted from proglacial lakes, water chemistry alone is not a reliable indicator of the origin of the clear basal ice. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Sues Glacier terminus; glacier ice; clear basal ice

1. Introduction

Studies of the solute chemistry of basal ice have been widely employed in investigations of thermal and mechanical processes in the basal ice zone (Hallet et al., 1978; Souchez and Lorrain, 1991; Souchez and Tison, 1981; Souchez et al., 1978). Most such

studies have focused on wet-based and polythermal glaciers have been widely studied and there have been few studies of dry-based glaciers.

Dry-based (polar) glaciers are characterised by an absence of englacial or basal melt water. Until recently, the absence of basal meltwater in these glaciers was thought to mean that basal sliding was not possible and that most movement was accomplished by internal deformation. The work of Echelmeyer and Zhongxiang (1987) has challenged this view and concluded that glacier substrates can deform at temperatures below zero. The most com-

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prehensive study of a dry-based glacier was completed by Holdsworth (1974) who identified a salt-rich ice layer close to the bed of the Meserve Glacier in the Wright Valley which he termed “amber” ice. He suggested that solid-state diffusion of dissolved solids from a salt-rich substrate may explain this phenomenon. Another report of salt-rich glacier ice in the Dry Valleys suggested entrainment of saline lacustrine sediments (Chinn 1987). More recently, Fitzsimons (1996) suggested that dry-based glaciers or ice sheet margins are capable of entraining blocks of sediment lake water by proglacial accretion of lake water and sediment. The quite different interpretations of the characteristics and origin of basal ice in dry-based glaciers shows that there is a clear need for a closer examination of individual ice facies.

The primary objective of this study was to undertake a reconnaissance survey of the chemistry of clear basal ice of six glaciers in the Dry Valleys to determine whether there is a difference between the chemical composition of glacier ice and basal ice. The secondary objective was to examine whether the chemical composition of basal ice reveals the process of basal ice formation, in particular whether it is likely that lake water has been accreted to the base of dry-based glaciers. This paper describes the field and laboratory methods used to study the chemical composition of the glacier ice and lake waters, describes the base cation and chloride concentrations and evaluates four hypotheses that may explain the observed patterns.

2. Field area and methods

The Taylor, Wright and Victoria valleys are part of the Dry Valleys, a polar desert in Southern Victoria Land, Antarctica (Fig. 1). Summer temperatures rarely exceed 0°C, while the mean annual temperature at Lake Vanda in the Wright Valley is -19.8°C (Schwerdtfeger, 1970). Rainfall is unknown, snowfall is light (ca. 10 mm water equivalent per year, Chinn 1990), and most of the area has a moisture deficit. In this study, five dry-based alpine glaciers: Lacroix, Suess, Canada, Clark and Victoria Upper glaciers and one piedmont glacier, the Wright Lower Glacier (Fig. 1), were examined. At each glacier, at least one sample of glacier ice and clear basal ice

were taken and where a proglacial lake was present, at least one sample of lake surface ice and lake water. A total of 14 basal ice samples, nine glacier ice samples, seven lake ice samples and seven lake water samples were analysed. Five aliquots of each sample were analysed in the laboratory (Table 1).

Basal ice samples were taken from the 1–2 m thick discoloured, debris-rich ice at the base of the glacier. Only the clear ice facies found in layers up to 20 mm thick and characterised by very low debris concentrations and low bubble concentrations were sampled. This ice facies is similar to clear basal ice described in other alpine glaciers by Sharp et al. (1994) and Hubbard et al. (1996). At each sample site, the outer 3–5 cm of ice and debris were removed before sampling and in the case of basal ice and ice from moraines, samples were taken from individual layers 5–10 cm thick that were characterised by low bubble and sediment concentrations. Samples of lake ice and water were taken near the terminus of those glaciers terminating in or near proglacial lakes. Ice samples were placed in clean polyethylene bags and water samples were stored in 250 ml polyethylene containers.

To minimise chemical dissolution caused by prolonged melting, all ice samples were melted and immediately filtered through 0.45 μm cellulose nitrate membrane filters, as outlined by Souchez et al. (1973). Each filtered sample was split into five 250 ml aliquots and stored in 250 ml polyethylene containers for subsequent laboratory analysis. All individual sample concentrations reported in this paper are averages of five determinations. Base cation concentrations were determined by atomic absorption spectrophotometry (AAS), using absorption mode for calcium and magnesium, and flame emission mode for sodium and potassium. The analysis were carried out on a Hitachi Z6100 AAS, using Zeeman background correction. Chlorides were analysed by flow-injection analysis (FIA), on a Tecator 5012 FIA, using the ferric thiocyanate method.

In order to evaluate the magnitude of ion exchange between meltwater and particles, prior to filtering, a series of experiments was undertaken. Glacier ice from the Suess Glacier was melted and mixed with known masses (0.1–1.5 g) of sediment which was mixed with the melted glacier ice and left to stand for periods of 5, 10, 30 or 60 min. The

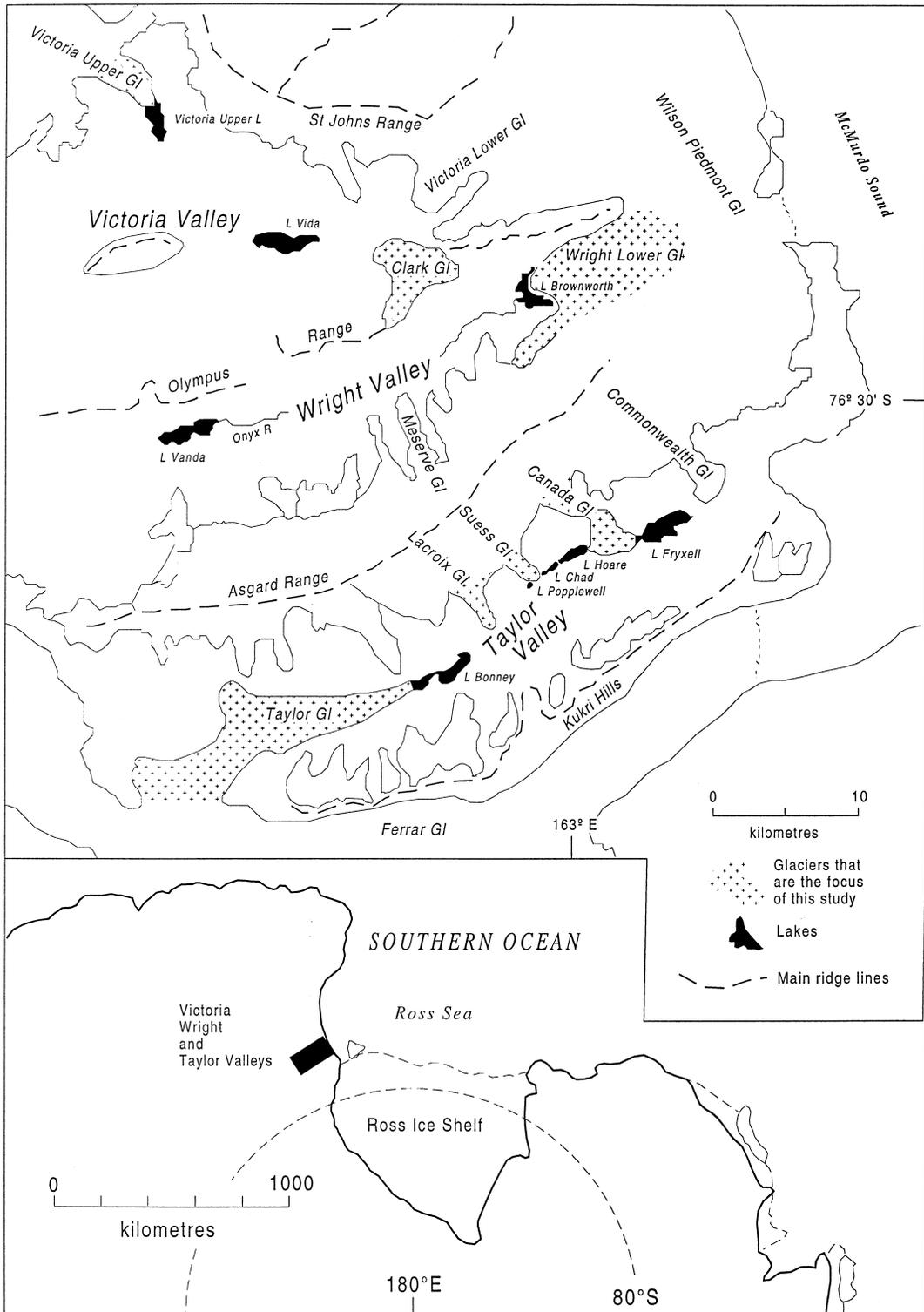


Fig. 1. Location of the Dry Valleys and the glaciers examined in this study.

Table 1
Mean base cation concentrations in the glacier ice and clear basal ice

Ice type	n ^a	Na	K	Ca	Mg	TDS	TDS (s.d.)
Glacier ice	9	0.90	0.54	0.71	0.09	2.24	1.01
Clear basal ice, Group 1	6	0.67	0.85	0.62	0.08	2.36	1.20
Clear basal ice, Group 2	7	2.52	1.21	1.25	0.24	5.21	1.10
Clear basal ice, Group 3	1	22.04	1.91	1.45	6.31	35.78	–

^aFive aliquots analysed for each sample.

water was then vacuum-filtered through 0.45 μm membrane filter and analysed using AAS.

3. Results

Only slight changes in the base cation concentration occurred in the laboratory experiments to test

the magnitude of ion exchange between sediment and meltwater as the ice samples were melted. The maximum increase in concentration over 60 min for a 1-l sample with 10 g of sediment was 1.1 ppm. Since all debris concentrations for the clear facies were less than 1 g l⁻¹, we conclude that there was minimal ion exchange at the debris concentrations and melting times used in this study.

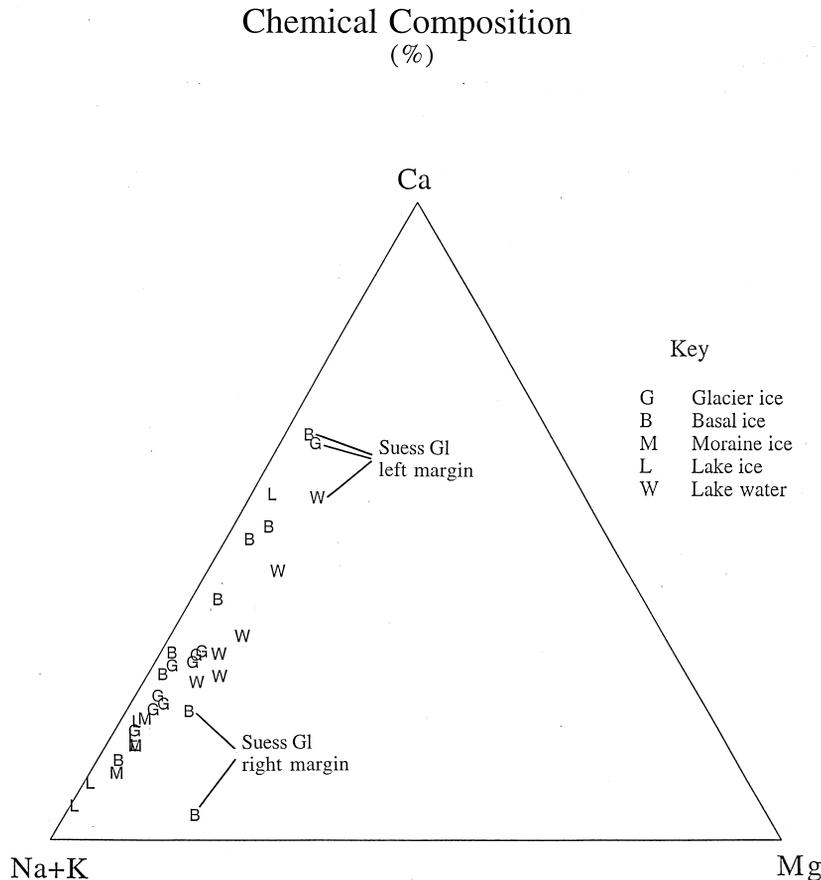


Fig. 2. Relative proportion of base cations in samples (%). Note: the scale for all axis is 0–100%.

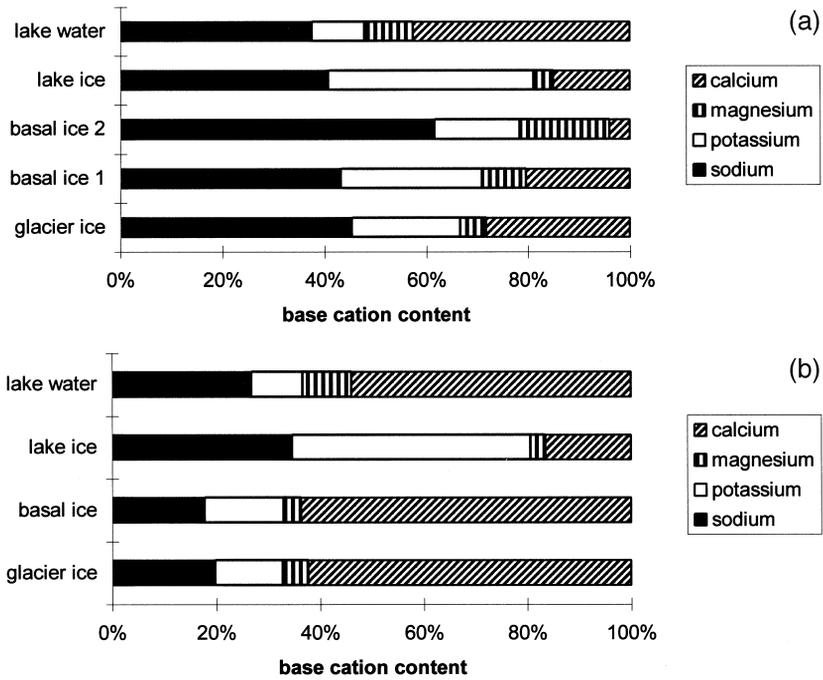


Fig. 3. Percent composition of base cations in samples from the Suess Glacier terminus at (a) the right margin and (b) the left margin.

The base cation composition of glacier ice, clear basal ice in the glaciers and moraines, and lake water and ice are summarised in Fig. 2. The greatest variability occurs in the sodium and potassium (Na + K) concentrations. All sites have a low magnesium (Mg) concentrations. Generally, lake water has the highest Na + K content followed by glacier ice,

moraine ice then lake water. The main exception to this trend is the left margin of the Suess Glacier adjacent to Lake Chad (Fig. 2).

The base cation composition of the clear basal ice is highly variable, particularly in the proportion of Na + K and Ca (Fig. 2). Samples from the core of moraines are very similar composition to basal ice

Table 2
Chemical composition of samples from the Suess Glacier terminus (ppm)
The total dissolved solids (TDS) is the sum of all the components.

Location	Sample	Na	K	Ca	Mg	Cl	TDS
<i>Right margin</i>	glacier ice	1.3	0.6	0.8	0.2	2.4	5.3
	clear basal ice	1.6	1.0	0.8	0.3	3.0	6.7
	clear basal ice	22.0	6.0	1.4	6.3	38.5	74.2
	lake ice	0.7	0.7	0.3	0.1	1.0	2.8
	lake water	5.3	1.5	6.2	1.3	6.7	21.0
<i>Left margin</i>	glacier ice	0.9	0.6	2.7	0.2	1.5	5.9
	clear basal ice	1.0	0.8	3.5	0.2	1.6	7.1
	lake ice	0.3	0.4	0.2	0.0	0.4	1.3
	lake water	3.1	1.1	6.2	1.1	6.0	17.5

samples. One basal ice sample from the right margin of the Sues Glacier adjacent to Lake Popplewell has a particularly high Mg concentration and high Na + K concentrations (Figs. 2 and 3). In contrast, basal ice samples from the left margin of the glacier show low Mg and Na + K concentrations and relatively high Ca concentrations. The variability of the Sues Glacier basal ice samples is clearly shown in Fig. 3.

Except for basal ice, sample 2 glacier ice from the Sues Glacier has a slightly higher Na content than basal ice. This pattern was observed in the data from all glaciers sampled in this study. The Na composi-

tion of basal ice sample 2 is 22 ppm, nearly 14 times greater than basal ice sample 1 (Table 2). A similar order of magnitude difference occurs in the concentration of Cl and Mg for the same sites. This sample also contained dissolved sulphites (Bob Wharton, pers. comm., 1997) which, together with accumulations of bacteria, suggest an organic origin. The variability between these clear basal ice samples and other ice facies is demonstrated by the total dissolved solid content. In this study, the TDS is the sum of Mg, Ca, Na, K and Cl (Table 2 and Fig. 4). TDS is used here as a surrogate for salinity since it is

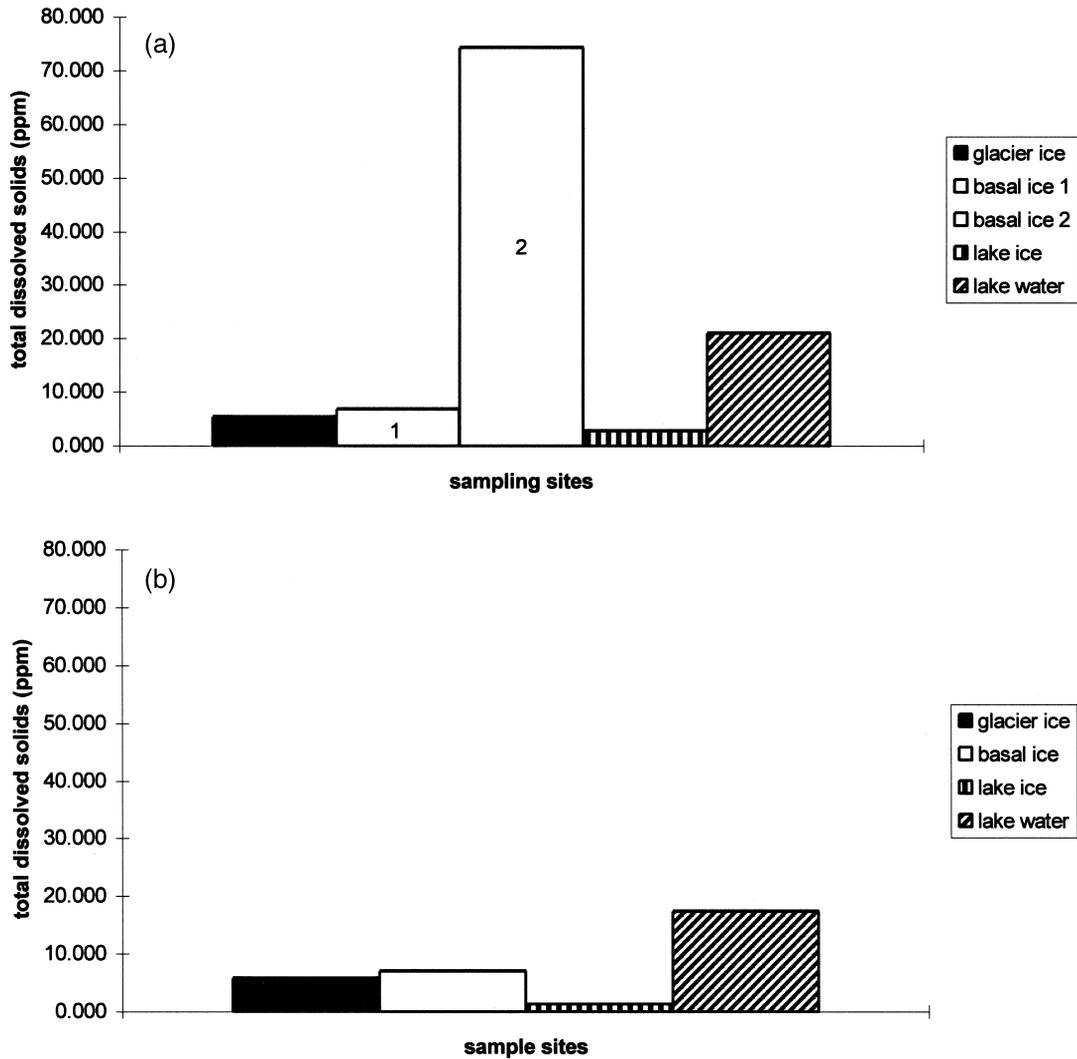


Fig. 4. TDS in samples from the Sues Glacier terminus at (a) the right margin and (b) the left margin.

a measure of the concentration of all dissolved salts (Miller et al., 1987).

At both the right and left margins of the Sues Glacier, the clear basal ice samples have a higher TDS concentrations than glacier ice which is characterised by elevated Na and Cl concentration (Table 2 and Fig. 4). This pattern was observed in all the glaciers studied, although the values varied substantially. In all the glaciers terminating in or near proglacial lakes, the TDS of basal ice was much higher than lake ice, but lower than lake water. Again, the only exception was the clear basal ice sample 2 from the Sues Glacier (Fig. 4).

4. Discussion

Table 3 shows the base cation concentrations of glacier ice samples from this study and results from the Meserve Glacier which is in the Wright Valley, Law Dome in East Antarctica and four glaciers from the Alps. The values for glacier ice samples from this study and from the Meserve Glacier are higher than values for the European glaciers and for the Law Dome sample. The higher values may reflect the proximity of the sea to the Dry Valleys glaciers and/or the presence of salts that are concentrated in soils and lakes as a consequence of the excess of sublimation and evaporation over precipitation.

The chemical composition of all clear basal ice samples are different from that of the overlying

glacier ice and the basal ice samples are characterised by relatively high Na and Cl concentrations. Three groups of samples can be identified on the basis of the solute concentrations (Table 4). Group 1 consists of six samples that have solute concentrations that are lower than the maximum value for glacier ice (4.38 ppm). These six samples from the Wright Lower (4), Canada (1), one the Lacroix (1) glaciers have an average base cation concentration of 2.36 and a standard deviation of 1.20 which is very similar to the composition of glacier ice (mean = 2.24, standard deviation = 1.01). These samples are considered to have no solute enrichment because they are indistinguishable from glacier ice. Group 2 consists of seven samples that have solute concentrations that have a mean base cation concentration of 5.21 and standard deviation of 1.10. The difference between Group 2 and Group 1 samples is statistically significant. Group 3 consists of one sample of clear basal ice from the Sues Glacier which had a base cation concentration of 35.78 ppm and a Cl concentration of 38.53 ppm which are more than 10 times the values of glacier ice.

For the purposes of comparison, Table 4 shows the concentrations of base cations and chlorides for the three groups of clear basal ice samples from this study, “amber” basal ice from the Meserve Glacier which is in the Wright Valley, clear basal ice from an ice cliff at the margin of Law Dome in East Antarctica and basal ice from four glaciers in the Alps. The solute concentrations of the single sample

Table 3

Base cation and chloride concentrations of glacier ice from the study compared to the Meserve Glacier, Law Dome and four glaciers from the Alps

Glacier	Samples	Na	K	Ca	Mg	Total	Cl
All glaciers (this study)	9	0.90	0.54	0.71	0.09	2.4	1.36
Meserve Glacier ^a	8	0.74	0.29	0.34	0.24	1.61	1.40
Law Dome (300 m) ^b	1	0.10	0.01	0.01	0.02	0.14	–
Glacier d' Argentiere ^c	8	0.16	0.22	0.25	0.08	0.71	–
Tsanfleuron Glacier ^d	11	0.07	0.07	0.33	0.02	0.49	–
Tsijiore Nouve Glacier ^e	18	0.02	0.04	0.08	0.03	0.17	–
Gruben Glacier ^e	11	0.03	0.04	0.07	0.03	0.17	–

^aHoldsworth (1974).

^bGoodwin (1988).

^cSouchez et al. (1973).

^dHallet et al. (1978).

^eSouchez and Lorrain (1978).

Table 4

Base cation and chloride concentrations of clear basal ice from the study compared to basal ice samples from the Meserve Glacier, Law Dome and four glaciers from the Alps

Glacier	Samples	Na	K	Ca	Mg	Total	Cl
This study, Group 1	6	0.67	0.85	0.62	0.08	2.36	1.26
This study, Group 2	7	2.52	1.21	1.25	0.24	5.21	3.77
This study, Group 3	1	22.04	5.99	1.45	6.31	35.78	28.53
Meserve Glacier (amber ice) ^a	6	7.58	1.61	5.68	–	14.87	–
Law Dome basal ice ^b	1	1.00	0.12	0.23	0.09	1.44	1.07
Glacier d' Argentiere ^c	9	2.24	2.29	0.71	0.28	5.52	–
Tsanfleuron Glacier ^d	9	0.05	0.08	1.35	0.06	1.54	–
Tsijiore Nouve Glacier ^e	13	0.07	0.09	0.13	0.04	0.33	–
Gruben Glacier ^e	13	0.09	0.13	0.28	0.05	0.55	–

^aHoldsworth (1974).

^bGoodwin (1988).

^cSouchez et al. (1973).

^dHallet et al. (1978).

^eSouchez and Lorrain (1978).

in Group 3 is considerably greater than all the basal samples from the Alps, clear basal ice from Law Dome and more than double the concentration of basal ice from the Meserve Glacier. Four mechanisms that may explain the observed patterns in the solute chemistry are melting and refreezing of basal ice, solid state diffusion, apron incorporation, and accretion of lake water to the base of glaciers as they advance into proglacial lakes.

Melting and refreezing at the glacier base is the most frequently cited mechanism to explain increased solute concentrations in basal ice layers (Souchez and Lorrain, 1978; Souchez and Tison, 1981; Souchez et al., 1978). These studies support Weertman's accretion hypothesis and Robin's heat pump theory, both of which require the temperature at the glacier base to be at or above the freezing point. Given that basal ice temperatures of the glaciers sampled in this study are well below freezing (-17°C in the Suess Glacier), regelation does not explain the elevated basal ice solute concentrations shown by the results.

The redistribution of solutes in a frozen state is a mechanism effective in very old ice and where very steep concentration gradients occur (Souchez et al., 1995). Holdsworth (1974) suggests that this is the main cause of elevated concentrations in the basal 5–6 m of the Meserve Glacier which is a dry-based glacier in the Wright Valley. In the case of the Meserve Glacier, Holdsworth argued that the diffu-

sion of ions was associated with diffusion of sediment from the glacier bed which give rise to the distinctive "amber" ice facies that is characteristic of the basal ice sequences of dry-based glaciers in the Dry Valleys area. The clear basal ice analysed in this study in all cases contained virtually no sediment and considerably less than the amber ice. It is unlikely that the solute signature of the clear basal ice derives from dispersal of fine-grained sediment. Although we cannot discount this mechanism on the basis of the available data, we believe that this mechanism does not provide an adequate explanation of the very high concentrations observed in clear basal ice samples.

The third potential mechanism that may explain the data is the apron entrainment model in which pre-existing ice at the glacier margin is incorporated in the basal zone as it is over-ridden. However, because basal ice formed in this way is primarily derived from calved blocks of glacier ice, it should have the same chemical composition as clean englacial ice. The results of this study show that the electrical conductivity of apron ice samples are nearly identical to values for clean glacier ice.

The fourth mechanism that requires evaluation is the proglacial lake ice/debris accretion model. Fitzsimons (1996) suggests that sediment blocks in the basal zone of some dry-based glaciers contain primary sedimentary structures, and algae layers that suggest that fluvial and lacustrine sediments have

been entrained at or near the ice margin together with a clear basal ice facies that may represent accreted lake water. Accretion of ice and debris are possible at ice margins terminating in proglacial lakes because relatively warm lake water keeps the surrounding sediment unfrozen. If ice is accreted as a glacier flows into a lake, the resulting ice would have a solute chemical signature related to the lake water although somewhat lower because of solute expulsion during freezing. An analogy of this system is the formation of surface ice on warm-bottomed lakes because the ice forms by freezing of the underlying water. The data from this study shows that lake ice exhibits considerably lower concentrations of total dissolved solids than the underlying water. In contrast, the solute concentrations in basal ice are much higher than the lake surface ice. Two possible interpretations are either that the basal ice is not derived from adjacent lake waters or the freezing process during ice accretion is such that a higher solute concentration is incorporated in basal ice than in the freezing process associated with the formation of lake surface ice. The latter alternative would be associated with conditions of rapid freezing of lake water to the glacier margin and slower freezing of lake surface water to produce surface ice. Although this scenario seems plausible, it is not possible to make a definitive conclusion on the basis of the available data.

5. Conclusions

The primary objective of this study was to determine whether the solute signatures of basal and englacial ice are different. The results show that in all the glaciers sampled, the solute concentrations of ice near the glacier base is higher than the overlying glacier ice. However, large variations in the values for different glaciers suggest that each glacier terminus should be examined as separate systems.

Four mechanisms for the ionic enrichment of basal ice samples have been examined. The regelation model is inappropriate because basal ice temperatures preclude the occurrence of meltwater at present. The solid-state diffusion model cannot be rejected, but it is difficult to see how it could produce the very high solute concentrations of ice samples

that contained no sediment. The apron-entrainment model is rejected because it does not explain solute enrichment of the magnitude that was observed. Lastly, although the data appear to be consistent with the proglacial lake ice/debris accretion model, the solute data alone do not provide a critical test of the model.

Although solute chemistry clearly distinguishes basal ice and indicates certain processes of formation, the actual processes cannot be determined from the chemistry alone. In the future, a valuable approach would be to conduct a detailed study of single glacier-lake system and an experimental study of changes in solute concentrations associated with freezing of proglacial lake water.

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