Ice Composition Evidence for the Presence of Liquid Water at the Base of Rhone and Taylor Glaciers, Antarctica

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INTRODUCTION

In a recent review Waller (2001) argued that there is a prevailing view in glaciology that sliding and bed deformation do not occur beneath cold based glaciers. Consequently it is believed that the ability of cold ice to erode the landscape is limited. Theoretical research by Gilpin (1979), Shreve (1984) and Fowler (1986) has suggested that sliding and regelation is possible at sub-freezing temperatures. The presence of liquid water under such conditions means much a higher potential for glaciers to erode their substrate and create landforms. Recent studies of the structure, composition and dynamic behaviour of small cold based alpine glaciers that occur in the McMurdo Dry Valleys strongly suggest that erosion can occur in subfreezing conditions. In addition, there is emerging evidence that liquid water plays at least some role in the development of basal ice sequences of cold based glaciers. In this paper, we describe a detailed study of the isotopic composition and solute chemistry of the basal ice sequences of Rhone and Taylor glaciers. The purpose of this work is to test whether liquid water played a role in the formation of the basal ice.

FIELD AREA & METHODS

Rhone Glacier (Figure 1) is a 13 km long alpine glacier that descends down the south-facing slope of the Asgard Range from an elevation of 2000 m and terminates 150 m above the valley floor where it rests on late Pleistocene deltaic sediments. Taylor Glacier is a 100-km long outlet glacier fed by Taylor Dome that occupies eastern portion of Taylor Valley before terminating at Lake Bonney. Mean annual temperatures between -14.8ºC to -30.0ºC mean that thin glaciers are likely to remain sub-zero year-round. Tunnels were excavated into the basal zones of both Rhone and Taylor glaciers near the glacier margins. Ice samples were taken with an electric chainsaw with tungsten carbide cutters. The ice blocks were sub-sampled in a cold laboratory maintained at -18ºC. Samples for solute and isotope analysis were taken every 50 mm. The laboratory analysis consisted of measurements of the stable isotopes ^{18}O and D and solutes Na, Mg, K, Ca, NH_4, Cl, F, NO_3, PO_3 and SO_4.

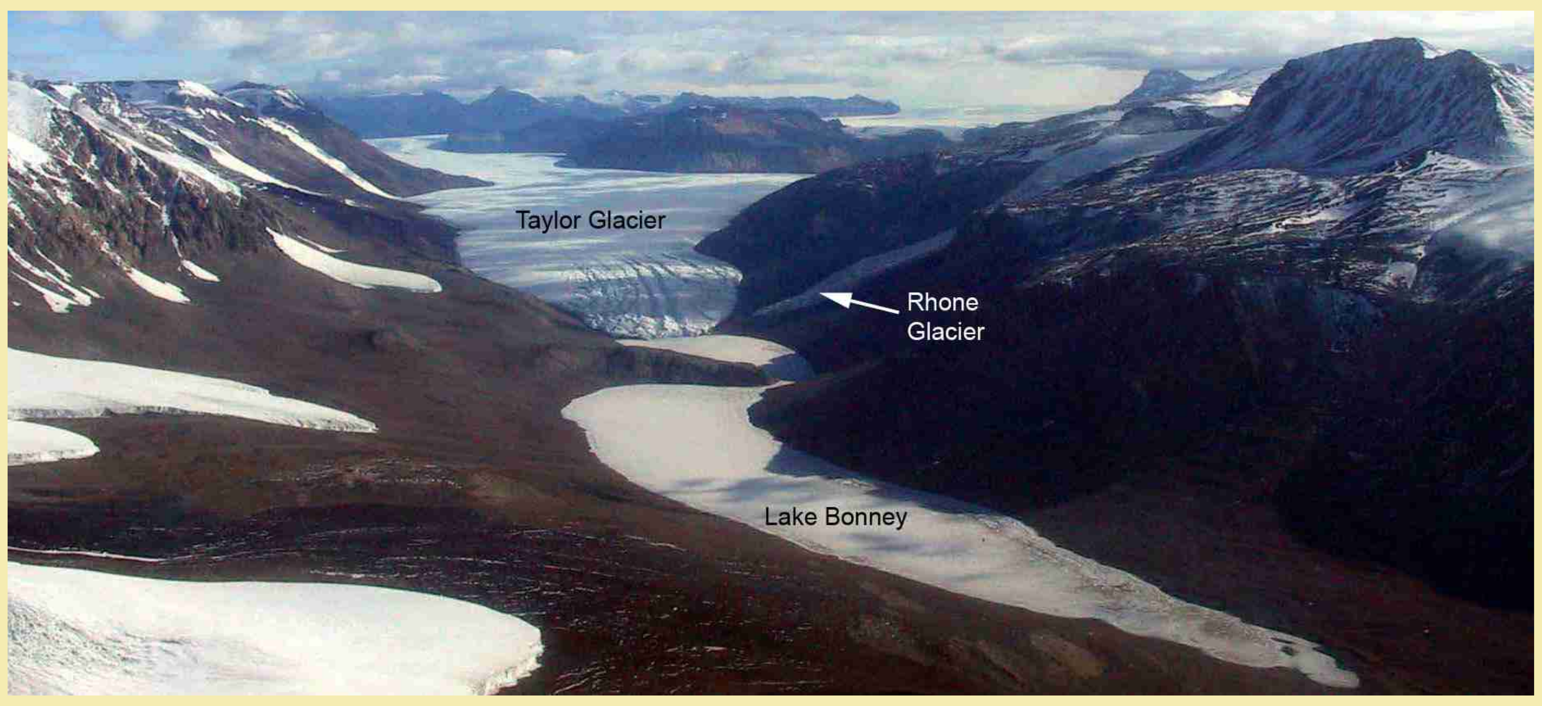

Figure 1: Photograph of the Taylor and Rhone glaciers, Taylor Valley, McMurdo Dry Valleys, Antarctica.

RESULTS

Three facies were identified in the basal ice sequence of the Rhone Glacier: stratified, amber and englacial. The amber facies is characterised by alternating dark and light bands with randomly distributed angular pebbles (Figure 2a) and solute concentrations averaging 30.7 ppm (Table 1). The stratified facies is characterised by a complex assemblage of alternating clean and debris-bearing layers (Figure 2b). The isotopic values of the stratified facies show a linear relationship described by $\delta D = 5.8\ \delta^{18}O - 73.7$ ($r^2 = 0.87$) (Figure 3). By contrast, the co-isotopic slope for the amber facies shows a linear relationship described by $\delta D = 8.4\ \delta^{18}O + 12.9$ ($r^2 = 0.93$) (Figure 3). The slope of 8.4 has a confidence interval of ± 0.23, which is statistically indistinguishable from the local meteoric water line (LMWL) of 8.1 from Lorrain et al. (1999).

Table 1: Solute concentrations for basal ice facies from Rhone Glacier in parts per million (ppm). Debris concentration is a percentage of volume.

Facies	Na	Mg	K	Ca	NH_4	Cl	F	SO_4	NO_3	PO_4	TDS	Debris Conc. (%)
Stratified	2.3	0.5	1.1	1.5	0.2	4.3	0.1	2.3	0.4	0.0	12.3	0.37
Amber	6.3	1.2	1.5	3.0	0.8	11.4	0.1	5.6	0.6	0.1	30.7	0.76
Clean	1.5	0.4	1.0	0.8	0.1	3.7	0.2	1.6	0.2	0.0	9.4	0.00

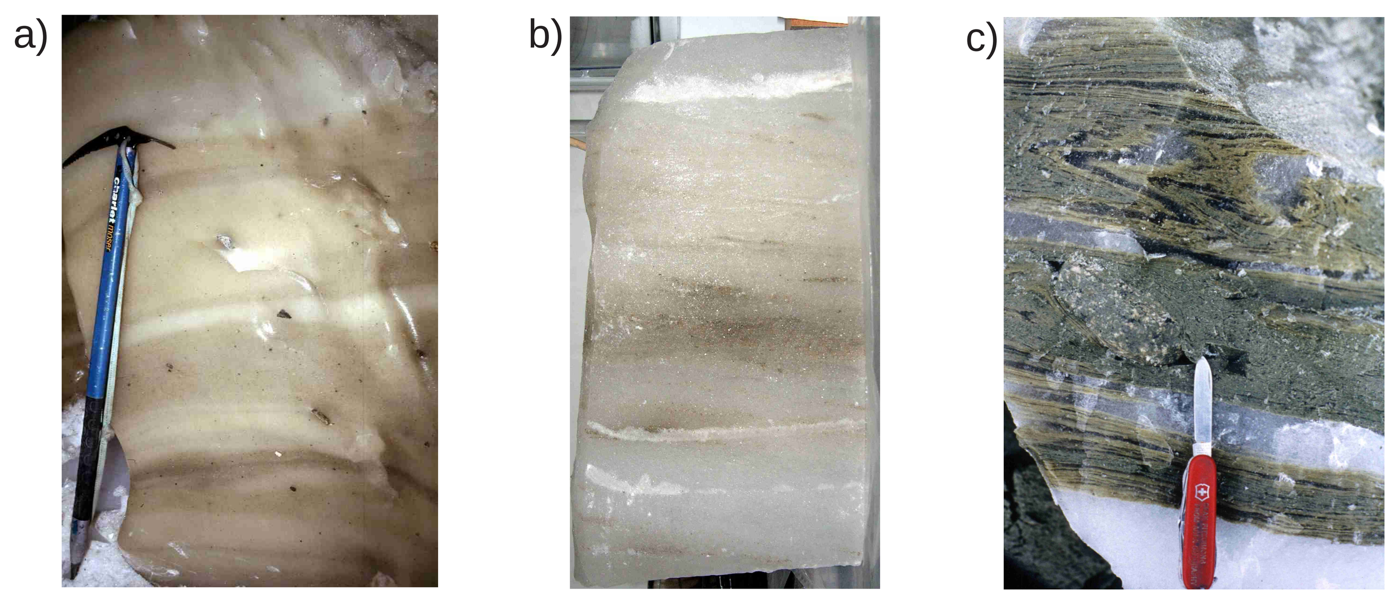

Figure 2: a) Amber ice in Rhone Glacier showing distinct light and dark bands and with numerous suspended pebbles. b) Stratified ice from Rhone Glacier which has layers of clean-clear, clean bubbly, and debris-bearing ice. c) Laminated ice from Taylor Glacier showing recumbent folds in alternating fine layers of clean, clear ice and debris-rich ice. The debris ranges in size from fine muds and silts, to large pebbles and cobbles.

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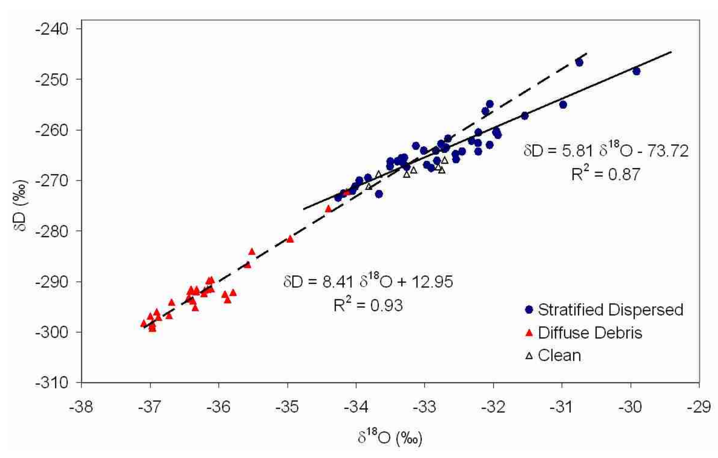

Figure 3: Coisotopic plot of the basal ice facies from Rhone Glacier. Amber facies plot on a slope of 8.4, compared to the stratified facies which plot on a slope of 5.8.

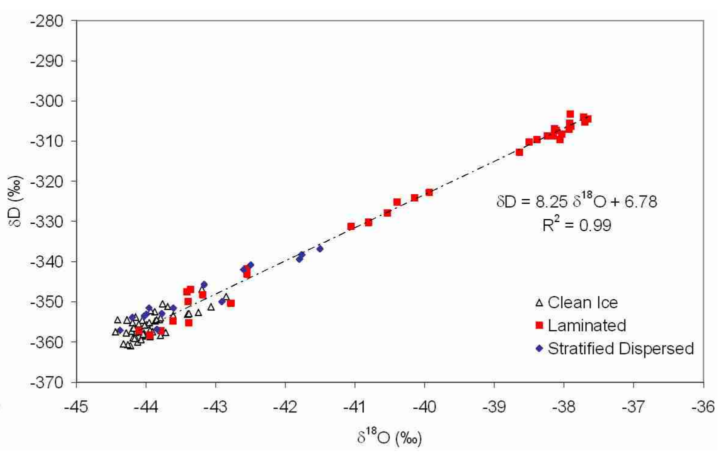

Figure 4: Coisotopic plot of the basal ice facies from Taylor Glacier. Laminated facies plot on a slope of 8.2, which is statistically indistinguishable from the local meteoric water line.

Two facies were identified in the basal ice sequence of Taylor Glacier: clean and laminated facies (Figure 2c). The clean ice has little or no debris, variable bubble content and low solute concentrations. The laminated facies is characterised by fine layers of clean clear ice and debris-rich layers and very high solute concentrations (2500 ppm). The debris is composed of mostly fine-grained material, with occasional pebbles with a debris concentration of 20% by volume. The basal ice from Taylor Glacier plots on an isotopic slope of $\delta D = 8.2\ \delta^{18}O + 3.8$ which is indistinguishable from the meteoric water line (Figure 4).

Table 2: Solute concentrations for basal ice facies from Taylor Glacier in parts per million (ppm). Debris concentration is a percentage of volume.

Facies	Na	Mg	K	Ca	NH_4	Cl	F	SO_4	NO_3	PO_4	TDS	Debris Conc. (%)
Clean	1.3	0.1	0.8	0.4	0.2	0.9	0.0	0.5	0.3	0.0	4.5	0.0
Laminated	503.7	82.5	232.0	611.6	0.4	313.3	1.4	938.6	0.3	0.0	2520.2	20.0

DISCUSSION

Coisotopic analysis of the amber facies (S = 8.4) demonstrates that the slope of the regression line is statistically indistinguishable from the LMWL (S = 8.1). This suggests that no liquid water was present when the amber facies formed. However, the amber facies is isotopically depleted compared to meteoric ice on average by 3‰ $\delta^{18}O$ and 25 ‰ δD. Such a pattern may be explained if the amber facies formed from meteoric processes when temperatures were cooler than present (e.g. LGM). Although the amber facies may have a meteoric origin its yellow-to-green colour together with its suspended, evenly dispersed sand and gravel grains clearly suggests that the ice has been in contact with the glacier bed where the solid and solute impurities have been entrained without apparent melting.

The regression line of the coisotopic values of the stratified facies has a slope of 5.8 ± 0.13 which is statistically distinguishable from the freezing slope of 5.5 (closed system) and 5.6 (open system). Our interpretation is that the stratified facies is formed by overriding of a marginal apron which would produce the admixture of clean bubbly ice, refrozen ice and debris observed in the stratified facies. Such an origin is consistent with the coisotopic analysis, which demonstrates that the δD-$\delta^{18}O$ slope lies between a freezing slope and the LMWL. This pattern would be produced if the stratified facies had a mixed origin, that is, some ice is derived from meteoric origin ice and the remainder from refreezing of meltwater on the apron surface. Indeed a close examination of Figure 3 shows that some of the stratified facies samples appear to have close affinity to the LMWL and others clearly plot on the line with a slope of 5.81.

Samples on the laminated ice plot on a slope of 8.2 which is statistically indistinguishable from the LMWL. This suggests that no liquid water was present when the laminated facies formed. However, this interpretation is at odds with the other physical characteristics of the ice, especially the high solute concentrations (2500 ppm) and debris concentration (20% by volume) and the ice structure, all of which sugges the ice has formed by melt and refreezing. It is possible that our results are an artefact of the sampling strategy. Our isotopic samples were cut at 8 mm thickness, and we believe this may be obscuring a regelation isotopic signature. Regelation processes occur on a millimetre to sub-millimetre scale, thus a complete freezing isotopic signature may not be apparent when ice is sampled at a 5 to 10 mm thickness.

CONCLUSIONS

Three principle conclusions can be made from this study:

1. The amber ice of Rhone Glacier appears to have formed from meteoric origin ice that has been in prolonged contact with the glacier bed. The coisotopic data suggests that the ice has formed in a cooler environment which suggests the ice may date to the LGM.
2. The coisotopic signature of the stratified facies in Rhone Glacier clearly demonstrates that liquid water played a substantial role in the formation of the ice. It appears that the ice has formed as the ice and debris apron together with refrozen meltwater has been overridden by the glacier terminus.
3. Ice from the base of Taylor Glacier remains a conundrum. While the ice has physical and solute characteristics consistent with a regelation origin, the isotopic data suggests that melt water has not played a role in the formation of the ice. It appears possible that the coisotopic analysis is an artefact of the sampling strategy. Future work should focus on whether fine scaled sampling will reveal a regelation signature in the laminated facies.

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