Stable isotope composition of the basal ice from Taylor Glacier, southern Victoria Land, Antarctica

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Summary A tunnel excavated into the margin of Taylor Glacier revealed a basal sequence containing a thick sequence of layers of clean clear ice and debris-rich ice which contained strong deformation features, as well as units of clean bubbly ice. Analysis of the isotopic composition of the basal ice shows a strong linear relationship that plots on a slope of 8, which is usually interpreted as meteoric in origin. However, the physical appearance of the laminated ice is inconsistent with a meteoric-origin interpretation and has the outward appearance of ice usually inferred as the product of basal melt-refreeze processes like regelation. We consider this apparent tension between physical appearance and isotopic composition of the Taylor Glacier basal ice to be a limitation of the stable isotope approach, and that the technique employed here is unable to diagnose small-scale processes like regelation.

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Introduction

Taylor Glacier is a large outlet glacier in the McMurdo Dry Valleys that is fed by Taylor Dome in the East Antarctic Ice Sheet. At its terminus, Taylor Glacier rests on unconsolidated sediments and has a basal ice temperature of -17^{o}C. Upstream of the terminus, the thermal conditions of Taylor Glacier are inferred to be at pressure melting point around 6 km upstream from the terminus (Robinson, 1984; Hubbard et al., 2004). Taylor Glacier has a thick basal sequence characterised by fine-grained sediments and iron-rich salt precipitates form the "Blood Falls" on its true left margin. The presence of both fine grained sediments and salts suggests that the basal zone of the glacier is interacting with the substrate, yet the mechanism of entrainment has not been explained. If Taylor Glacier is in fact polythermal, then accretion of salts and debris is normally interpreted as the result of small amounts of basal ice melt and refreeze which traps impurities in the ice. The process of melt-refreeze through either regelation or net adfreezing processes at the sole of the glacier should result in fractionation of the stable isotopes of water which have different thermodynamic properties across phase-change boundaries. The aim of this paper is to use stable isotope analysis to examine the role of liquid water in producing the basal ice sequences, and evaluate whether there is evidence for regelation or net adfreezing processes occurring under Taylor Glacier.

Basal ice Observations

A 20 m tunnel was excavated from the true left margin of the Taylor Glacier. Examination of the basal ice reveals three ice facies: stratified dispersed, laminated, and clean. The stratified facies extends from 0 to 0.7 m, and is overlain by a 0.7 m-thick layer of clean facies. At 1.5 m to 2.8 m is a thick layer of laminated facies. From 2.8 to 3.9 m are alternating layers of dispersed debris facies, clean facies and laminated facies. The stratified dispersed facies has a very low debris concentration (0.1% by vol.), low bubble concentrations, and an elevated solute concentration (183 ppm). The clean facies has little or no debris, variable bubble concentrations where some layers have relatively few bubbles that are distended parallel to flow, whilst other layers are bubbly. The clean facies also has very low solute concentrations, averaging 4.5 ppm. The laminated facies exhibit strong foliation, recumbent folds, shearing and faulting. The laminated facies has a debris concentration of 25 % by volume and are mostly comprised of mud-sized sediments, but sands and pebbles also occur. The solute content of this facies averages 2500 ppm. The basal zone reveals a sequence that is a mixture of ice that is clean ice and strongly modified ice that has high debris and solute concentrations (laminated facies). To understand the development of the basal ice sequence, the ice was sub-sampled and the stable isotope (δD and $\delta^{18}O$) composition was measured.

Stable isotope data

The use of stable isotope analysis by Jouzel and Souchez (1982) and Souchez and Jouzel (1984) have shown through both theoretical and experimental observations that the progressive freezing of a water reservoir plots on a slope that is distinct from the meteoric water line. Sequential freezing causes the reservoir to be gradually depleted in heavy isotopes. When δD plots against $\delta^{18}O$ for sequentially frozen samples, there is a decrease in the slope relative to a meteoric water line. Such a slope is referred to as a "freezing slope" and it is significantly lower than a meteoric water line because the ratio of the isotopic fractionation coefficients $(\alpha-1)/(\beta-1)$ is less than 8. The actual slope is also dependent on the initial isotopic signature of the parent material and is the basis for distinguishing between meteoric-origin ice and refrozen ice at the base of glaciers (Jouzel and Souchez, 1982). Ninety-six samples from the basal zone of Taylor Glacier were sampled at 50 mm intervals, and 8-10 mm slices of ice were taken for co-isotopic analysis. Isotopic analysis was undertaken using reduction over hot chromium for δD and reduced in a nickelised carbon column for $\delta^{18}O$, and has a precision of 0.1 ‰.

Analysis of the stable isotope data from Taylor Glacier revealed a range in isotopic values from $\delta^{18}O$ -44‰ to -37‰ and δD -360‰ to -303‰ and that the greatest range in values occurs within the laminated facies. A co-isotopic plot of all the data points from the basal ice has a strong linear correlation with a regression equation of $\delta D = 8.18 \pm 0.01\ \delta^{18}O + 3.78$ (r^2 =99%, n = 98) (Figure 1). Taylor Dome at the head of the Taylor Glacier, has a calculated local meteoric water of $\delta D = 7.79\ \delta^{18}O - 3.68$ (r^2 = 99%, n = 300) (Derived from data published by Steig and White, 2003). By comparison the local meteoric water line for Suess Glacier in Taylor Valley was reported by Lorrain et al. (1999) with a slope of 8.1.

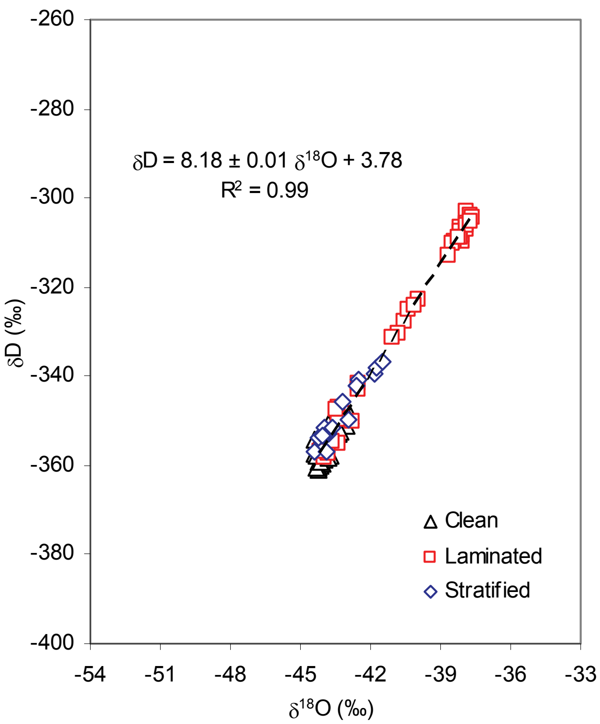

Figure 1. Co-isotopic plot of basal ice samples from Taylor Glacier. Samples plot on a slope of 8.18.

The basal ice samples from Taylor Glacier plot on a slope of 8.18 ± 0.01 which is statistically indistinguishable from the local meteoric water line for Suess Glacier. On this basis, the basal ice from Taylor Glacier could be interpreted as meteoric-ice. Such an interpretation is at odds with the physical appearance of the ice, particularly the laminated facies which is strongly altered in appearance from meteoric-origin ice and appears to be the product of a refreezing process. To examine the origin of the laminated facies, the data was divided into the three facies and regression analysis run on this basis. A line of $\delta D = 8.25 \pm 0.01\ \delta^{18}O + 6.78$ (r^2 = 98%, n = 34) describes the laminated facies, which is statistically indistinguishable from meteoric-origin ice. The stratified dispersed facies plot on a slope of δD = 6.99 ± 0.34 (r^2 = 92%, n = 15), and the clean facies lot on a slope of 6.60 ± 0.80 (r^2 = 51%, n = 49). According to the stable isotope model proposed by Jouzel and Souchez (1982) and Souchez and Jouzel (1984) the Taylor Glacier has a calculated freezing slope of 5.0 for a closed system and 5.5 for an open system. Thus the slopes of 7.0 and 6.6 for the stratified dispersed facies and clear facies fall between a freezing slope and meteoric slope.

Interpretation of stable isotope data

The basal ice from Taylor Glacier has an isotopic signature that is difficult to interpret with the stable isotope model described by Jouzel and Souchez (1982) and Souchez and Jouzel (1984). The approach of Jouzel and Souchez describes a two-ended model, where ice is either altered through melt-refreeze and plots on a freezing slope, or is unaltered and plots on a meteoric water line. In the case of Taylor Glacier this is unsatisfactory as it fails to explain the altered physical appearance of the laminated facies, and provides no interpretation for co-isotopic slopes that plot between freezing slopes and meteoric slopes. Confronted with a similar issue, Hubbard and Sharp (1995) suggested an alternative model for interpretation using "freezing envelopes". Hubbard and Sharp (1995) suggested that within any environment there will be a range in the isotopic composition of meteoric samples as a result of different atmospheric processes. Thus, there will be a range in the isotopic composition of parent material which will create a range of potential freezing slopes. The range of isotopic parent materials and freezing slopes can be modelled as an envelope of all possible variations by selecting the minimum and maximum values that naturally occur in the system, and then plotted as an "envelope".

A freezing envelope for the Taylor Glacier was constructed to examine whether the data from the Taylor Glacier had undergone freezing using data from the Taylor Dome (Steig and White, 2003). The lightest (-46.7‰) and heaviest (-36.8‰) $\delta^{18}O$ values were used to calculate theoretical upper and lower freezing slopes. The lightest meteoric sample produced freezing products between –44.1‰ and -49.3‰ (k = 0. 1 and k = 0.9) and a theoretical freezing slope of $\delta D = 4.8\ \delta^{18}O - 140.6$. The heaviest meteoric sample produced freezing products between -34.2‰ and -39.4‰ and a freezing slope of $\delta D = 5.4\ \delta^{18}O - 91.9$. By applying this isotopic freezing envelope to the Taylor Glacier data (Figure 2), the basal ice values plot along the right side of the envelope. Meteoric origin data plots along a line 3‰ less than the right

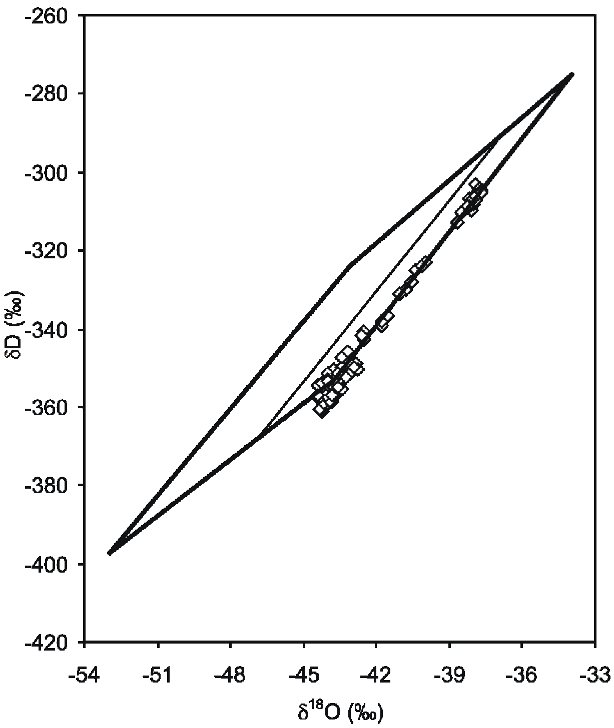

Figure 2. Theoretical freezing envelope for Taylor Glacier based on highest and lowest isotopic pairs from Taylor Dome meteoric samples. Basal ice samples (diamonds) plot on the extreme right of the envelope, whereas meteoric water line (light line) is offset by 3‰.

hand line, as this line represents ice that is enriched in the early stages of freezing. Thus using the freezing envelope approach the basal ice sequences from Taylor Glacier are consistent with ice that has formed at the initial stage of freezing and is relatively enriched in heavy isotopes. If the basal ice samples have formed by the interaction of water as suggested by the freezing envelope model, this raises questions over the validity of the current statistical based mode of interpreting co-isotopic data on a slope coefficient.

Regelation processes occur on a scale of only millimetres and that a single freezing event may only be a few millimetres in thickness (Hubbard and Sharp, 1989; 1993). If the individual ice laminae formed by regelation are 0.1 to 1 mm in thickness as suggested by Hubbard and Sharp (1995), each millimetre-thick laminae reflects one complete freezing event. To observe fractionation sampling would need to occur at a sub-millimetre level. In this study, as in all reported co-isotopic studies, samples were 8 to 10 mm in thickness so if regelation occurred it may not show a change in co-isotopic slope, but there appears to be some evidence of an isotopic shift using the freezing envelope approach suggested by Hubbard and Sharp (1995). If regelation occurs on a sub-millimetre level, isotopic analysis may not be able to distinguish between meteoric origin ice and refrozen ice. If the Taylor Glacier is at pressure melting point as theorised by Robinson (1984) and Hubbard et al. (2004), then regelation is likely to occur as the glacier bed changes from wet-based to cold-based conditions. The accretion of fine-grained material into thin laminations as observed in the basal ice of the Taylor Glacier is consistent with small-scale freezing at the glacier sole. The interpretation of refrozen isotopic signature (even on a slope of eight) may in fact, be consistent with regelation at the glacier sole. This interpretation however, requires further work to see whether isotopic fractionation can be measured in regelation ice at sub-millimetre thickness.

Conclusion

The isotopic composition of the basal ice from Taylor Glacier plots on a slope of 8.1 which is statistically indistinguishable from the local meteoric water line. However, when this data is plotted on a "freezing envelope" as proposed by Hubbard and Sharp (1995), the samples plot in the enriched portion of the envelope that suggests that the ice has undergone melt and refreeze and become relatively more enriched in heavy isotopes. Such enrichment usually occurs at the initial stages of freezing, and suggests that the basal ice samples have in fact experienced melt-refreeze despite plotting on a slope of 8. This study has highlighted the difficulties on applying the strict statistically-based co-isotopic approach to the basal ice samples, and fails to adequately shed light on the entrainment processes active at the ice-substrate interface of Taylor Glacier.

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