Micro-Scale Isotopic Analysis of Ice Facies Frozen from Supercooled Water

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ABSTRACT. Subglacial glaciohydraulic supercooling can form basal ice and affect glacier dynamics, sediment transfer and geomorphology. Whilst isotopic analysis ($\delta^{18}O$-δD) of basal ice has demonstrated the significance of supercooling, questions remain as to what extent the identification of supercooling depends on sampling resolution. We conducted laboratory experiments in which ice was frozen from supercooled water and sampled at a micro-scale (1.5 millilitre) to identify highly localised variations in isotopic compositions that might be lost in bulk-scale sampling. Three distinctive ice facies produced by the freezing process demonstrated diagnostic isotopic signatures that were distinguished when the facies were sampled independently. However, their respective isotopic signatures were lost when bulk-scale sampling combined the two facies, demonstrating the requirement of micro-scale sampling when identifying supercooling in basal ice facies. These findings indicate that sampling for isotopic compositions of ice facies frozen from supercooled water should be conducted at a scale that prevents the amalgamation of different facies to highlight a detailed isotopic signature. We conclude that micro-scale sampling is imperative to understanding and quantifying this subglacial process.

Keywords: supercooling, isotopes, sample size, freezing slopes.

1.0 Introduction

Glaciohydraulic supercooling occurs when basal water at, or below the pressure melting point ascends from a subglacial overdeepening and the water temperature rises quicker than the water which is heated by viscous dissipation (Alley et al. 1998; Lawson et al. 1998). Where it occurs, supercooling can lead to the accretion of ice at the base of glaciers even where the basal thermal regime is temperate, and provides a mechanism for the creation of debris-rich basal ice in those temperate settings. Supercooling was found to be the primary formational process of stratified basal ice at the Matanuska Glacier, Alaska (Alley et al. 1998; Lawson et al. 1998; Evenson et al. 1999; Ensminger et al. 2001; Larson et al. 2010; Larson et al. 2016). At other temperate glaciers which could support supercooling, the Matanuska-type model has been shown to be less efficient with regards to basal ice formation elsewhere (Spedding and Evans, 2002; Swift et al. 2006; Cook et al. 2007; 2010; Swift et al. 2018). For example, Cook et al. (2010) determined supercooling only formed 42% of the stratified basal ice facies at Svínafellsjökull, Iceland.

Ice formed from supercooled water is known to be isotopically (δ^{18}O-δD) lighter relative to the parent water, but the extent to which this occurs is unknown (Lawson et al. 1998; Ensminger et al. 2001; Cook et al. 2010; Larson et al. 2010). Cook et al. (2010) found at Svínafellsjökull that the isotopic composition of anchor ice frozen from supercooled water was lighter by ~2.4‰ in δ^{18}O and 15.2‰ in δD relative to the subglacial upwelling. Larson et al. (2010) concluded that supercooling at Vatnajökull and Öræfajökull, Iceland was the primary formational process for the stratified basal ice facies because it was lighter by ~2.4‰ in δ^{18}O and 12‰ in δD relative to the vent water. Thus, whilst we understand the isotopically light nature of stratified basal ice formed from supercooling, a lack of detailed knowledge remains surrounding the specific mechanisms and levels to which this occurs.

Methods used to quantify supercooling consist of visual, sedimentological, stable isotope and radionuclide analysis (e.g. Alley et al. 1998; Lawson et al. 1998; Evenson et al. 1999; Titus et al. 1999; Ensminger et al. 2001; Roberts et al. 2002; Spedding and Evans. 2002; Swift et al. 2006; Cook et al. 2007; 2010; Larson et al. 2010; Cook et al. 2011; Swift et al. 2018). Here, we focus on the importance of sample scale for stable water isotope analysis of ice facies frozen from supercooled water. Water isotope analysis has frequently been used as a quantification method when evaluating the significance of glaciohydraulic supercooling (e.g. Lawson et al. 1998; Titus et al. 1999; Ensminger et al. 2001; Swift et al. 2006; Cook et al. 2010; Larson et al. 2010). Sample sizes of basal ice formed from supercooling collected at glaciers for isotopic analysis range from 25-300 mL (Titus et al. 1999; Ensminger et al. 2001; Swift et al. 2006; Cook et al. 2010; Larson et al. 2010). However, due to their large sizes, these basal ice samples could contain ice facies formed from multiple alternative processes. This amalgamation of different ice facies could dilute the isotopic fingerprint of supercooling, potentially leading to an inaccurate diagnosis of basal ice formation. This study develops on comments from Cook et al. (2010) suggesting the scale in which basal ice samples are collected will be important as bulk-scale sampling could homogenise the isotopic signatures of formational processes.

Basal ice investigations separate from supercooling have also considered their sample sizes. Hubbard and Sharp (1993) illustrated if the basal ice layer is sampled with a cylindrical sampler that has a diameter of 2 cm, it could incorporate several layers of laminated facies, instead of a single layer of ice. Souchez and De Groote (1985) sampled basal ice samples at the base of Grubengletscher that were placed in 30 mL glass bottles. Souchez et al. (1998) revised a sampling strategy developed by Souchez and DeGroote (1985), collecting samples at a resolution of 1 mL instead of 30 mL from five Arctic glaciers. A fractional melting experiment was applied from Russell Glacier and demonstrated the lack of fractionation by sampling 25 mL of melt water. The clustering of samples on co-isotopic plots (δ^{18}O-δD) suggested there was no fractionation during basal ice formation by regelation, or the scale of the sample had homogenised the isotopic compositions (Souchez et al. 1988).

This study takes a laboratory-based approach to investigate whether field studies of basal ice evaluating glaciohydraulic supercooling should consider a micro-scale approach to sample size collection at glaciers. Replicating supercooling conditions under laboratory conditions has been performed in three studies to date (Knight PG and Knight DA, 2005; 2006; Cook et al. 2012). The overarching similarity found by the studies was a distinct 'herringbone' crystal structure associated with supercooling (Figure 1). This diagnostic crystal structure forms as a result of multi-directional ice growth during freezing from supercooled water (Knight PG and Knight DA, 2005). Thus, ice frozen from supercooled water will henceforth be referred to as 'herringbone ice'. In order to determine whether bulk-scale sampling of ice frozen from supercooled water yields the same isotopic composition as a micro-scale sampling approach, four laboratory experiments were performed in a closed-system.

[Figure 1 near here]

2.0 Methodology

We sampled and melted ice frozen from supercooled water on a 1.5 mL scale to identify any micro-scale isotopic differences in basal ice facies. Our aim was to determine whether bulk-scale sampling resolves the same isotopic composition for the ice facies frozen from supercooled water as the micro-scale sampling technique. Four laboratory experiments were conducted, with the sampled ice isotopically and statistically analysed.

2.1 Replicating Supercooling Conditions

We followed previous methodologies which have replicated supercooling conditions (Knight PG and Knight DA 2005, 2006; Cook et al. 2012), where a small recirculating pump (flow-rate 1400 litres per hour) was clamped to the side of an open, plastic container (16x36x27 cm) half filled with tap water to a depth of 8 cm in a cold laboratory at -12 ^{o}C. The tap water had a temperature of 11 ^{o}C at the beginning of each experiment before being placed in the cold laboratory. This setup stimulated supercooling, keeping the water turbulent and allowing it to drop below 0 ^{o}C without freezing. The pump was switched on and the experiment was left for five days. On the fifth day, the pump was switched off to allow the remaining supercooled water to freeze (Figure 2). After the seventh day, the ice block was removed from the container and separated into its respective facies. The experiment was conducted four times across a four-week period, accumulating 84 samples in total. 28 samples of each facies (clear, herringbone and mixed) were sampled and analysed (Figure 3).

[Figure 2 near here]

[Figure 3 near here]

2.2 Micro-Scale Sampling

We applied a biased sampling strategy where the facies were sampled based on their crystal structure. Once the ice types had been categorised into their facies, they were carefully cut by a bandsaw to allow for micro-scale sampling. The samples were placed on the bandsaw in the cold laboratory at -12 ^{o}C and were pushed through the blade to create the thin sections in preparation for melting. The facies were visually identified and separated precisely using the bandsaw, ensuring that the ‘supercooled’ sample only contained the herringbone crystal structure. The mixed ice facies was sampled to combine both the herringbone and clear ice, in order to determine whether this amalgamation of facies would homogenise the isotopic composition of the herringbone ice. After thin-sectioning, samples were immediately placed into sealed plastic centrifuge tubes and moved to a room with a temperature of 15 ^{o}C to allow the samples to melt, ensuring no pre-melting.

2.3 Isotopic Analysis

The 84 samples from the four experiments were placed in vials and analysed in the Keele University ICELAB with a Los Gatos Research (LGR) Triple Isotope Water Analyser-DLT-EP, model 912-0032. The samples were measured at a precision of ± 0.4 for δD and ± 0.1 for δ^{18}O. Samples were interleaved such that a manufacturer standard was measured every ten samples. After being measured, sample data was exported to LGR’s post-processing software to calibrate the measured samples against the included LGR-supplied standards. We included standards that covered the isotopic range of the measurements taken. The standards used, and their specifications are as follows:

- LGR2C: δD = -123.7 ± 0.5‰ vs VSMOW: δ^{18}O = -16.24 ± 0.15‰ vs VSMOW
- LGR3C: δD = -97.3 ± 0.5‰ vs VSMOW: δ^{18}O = -13.39 ± 0.15‰ vs VSMOW
- LGR4C: δD = -51.6 ± 0.5‰ vs VSMOW: δ^{18}O = -7.94 ± 0.15‰ vs VSMOW

2.4 Freezing Slopes

Regression slopes between δ^{18}O and δD (known as ‘freezing slopes’) can give insights into refrozen water and water sources incorporated in the system and the associated fractionation. For example, depending on the gradient of a freezing slope, it can be determined whether the input of water into a system has a similar isotopic composition as the initial reservoir. Consequently, freezing slopes can be used as a method of determining basal ice formation. Hypothetically, if a basal ice facies formed from an initial water which had a slope of 6.7, and a second facies formed from a different water source with a slope of 7.5, it indicates that these two facies formed from distinctly different water sources because of the different slopes. However, if both facies yielded an identical freezing slope of 6.7, it would suggest that the facies formed from the same initial water and process.

As we conducted stable isotope analysis in a closed-system, the freezing slope model determined by Jouzel and Souchez (1982) was utilised (Equation 1). This was achieved by using the isotopic composition of the initial reservoir to determine the gradient of our freezing slopes.

$$S = [(\alpha - 1)/(\beta - 1)] \times [(1000 + \delta D)/(1000 + \delta^{18}O)] \qquad (1)$$

Where S is the gradient of the freezing slope, α and β are the equilibrium fractionation coefficients for deuterium and ^{18}O respectively (Jouzel and Souchez, 1982). We chose values for our equilibrium coefficients from Lehmann and Siegenthaler (1991), who conducted high precision measurements of the isotopic fractionation of ice grown on a cooling plate from an agitated water mass. They calculated that '*α*' had a value of 1.0212 and '*β*' had a value of 1.00291. The closed-system models were applied to the experiments to determine whether the models would predict the freezing slopes. Freezing slopes will have a shallower gradient than the Global Meteoric Water Line (GMWL) which has a gradient of 8 on a δD-$\delta^{18}O$ co-isotopic plot. The GMWL is used as a comparison standard in this analysis rather than the Local Meteoric Water Line (LMWL), because tap water was used as the source.

3.0 Results

3.1 Experimental Observations

Three facies froze in the four isolated experiments:

- Facies 1) Clear ice (frozen at 0 °C)
- Facies 2) Herringbone ice (artefact of supercooled water: frozen below 0 °C)
- Facies 3) Mixed ice (containing the herringbone and clear crystal structures)

The mixed ice facies contained both the herringbone and clear facies. It was treated as a proxy for the bulk-scale sampling utilised in previous research, as it contained more than one ice type. The herringbone ice has been suggested to be indicative of closed-system supercooling freezing under laboratory conditions (Knight PG and Knight DA 2005, 2006; Cook et al. 2012). The herringbone facies formed at the lowermost section of the container as this layer was nearest to the recirculating pump where the turbulence was at its strongest, preventing freezing. The thickest layer was the mixed ice as it contained two crystal structures (clear and herringbone) in the middle section of the container. The clear facies froze as a relatively thin layer above the boundary of the mixed facies because the turbulence had minimal impact at the uppermost layer of the container.

3.2 Isotopic Analysis

Co-isotopic diagrams were constructed to highlight isotopic differences in the documented facies (Figure 4). The facies mean isotopic values, freezing slopes and adjusted R^2 coefficients can be seen in table 1. We report the adjusted R^2 values to show goodness of fit for the freezing slopes. The lowest adjusted R^2 value is 0.93 for experiment 3, indicating a strong agreement between the freezing slopes and the measured isotopic values for all four experiments. The clear facies was the isotopically lightest facies relative to the initial reservoir. The clear facies in experiment 1 was lighter by -12.4‰ in δD and -1.8‰ in δ^{18}O relative to the parent water. The mixed facies was isotopically heavier than the initial water, e.g. -12‰ in δD and -1.6‰ in δ^{18}O in experiment 1. The herringbone facies was the isotopically heaviest facies compared to the initial water, e.g. heavier by -32‰ in δD and -4.5‰ in δ^{18}O in experiment 1. This trend continued throughout the remaining three experiments, with the clear ice being the isotopically lightest, the mixed facies being heavier, and the herringbone ice being the heaviest. The clear facies isotopic compositions ranged by -14‰ for δD and -2.5‰ for δ^{18}O across the four experiments. The mixed ice varied by -13.7‰ in δD and -2.3‰ in δ^{18}O and the herringbone facies had an isotopic range of -22‰ for δD and -3.8‰ for δ^{18}O across the four experiments. The parent water isotopically varied by -0.4‰ in δD and -1.6‰ in δ^{18}O.

[Figure 4 near here]

[Table 1 near here]

These variations in the δ^{18}O compositions resulted in experiments 3 and 4 parent waters not plotting directly on the GMWL, suggesting the water had been modified isotopically from its meteoric source. Variations in parent water are important as they can result in an ice facies having a heavy or light isotopic composition, having implications for the statistical difference between facies. For example, the parent water in experiment 1 had a lighter δ^{18}O value (-7.7‰) compared to experiment 3 (-6.1‰). Consequently, the facies which formed in these individual experiments had contrasting compositions in their δ^{18}O values.

3.2.1 Deuterium Excess

Across the four experiments, the herringbone ice had the heaviest deuterium excess values compared to the other facies and the clear ice had lightest values (Figure 5). The mixed facies plotted between the clear and herringbone facies in each experiment when placed on deuterium excess-δD diagrams.

[Figure 5 near here]

3.3 Freezing Slopes

The freezing slopes were not predicted by the Jouzel and Souchez (1982) closed-system model. For example, experiment 3 had a freezing slope of 5.95, yet a slope of 7.74 was predicted (Table 2). The freezing slopes had high adjusted R^2 values, ranging from 0.93 (experiment 3) to 0.99 (experiment 1 and 2), suggesting the slopes are a good fit for our data across all the experiments.

[Table 2 near here]

3.4 Analysis of Variance Testing

Analysis of variance (ANOVA) testing determines the statistical difference between individual parameters. A one-way ANOVA test was conducted for the four experiments to determine whether the documented facies were significantly different isotopically. After analysis and Tukey’s post-hoc comparisons of the facies’ mean value, the isotopic compositions of the documented facies in in all four experiments were statistically different from each other (p values < 0.005), and we can assert with 95% confidence that the clear, herringbone and mixed facies are significantly different (Table 3).

[Table 3 near here]

4.0 Discussion

4.1 Implications for Glaciohydraulic Supercooling Studies

Our results suggest that bulk-scale sampling of ice facies frozen from supercooled water could be overlooking micro-scale isotopic differences. This is evident as the herringbone facies is significantly isotopically distinct from the mixed facies (95% confidence – p values < 0.005). Consequently, previous studies investigating glaciohydraulic supercooling which bulk sampled basal ice facies may have lacked methodological precision (e.g. Titus et al. 1999; Ensminger et al. 2001; Swift et al. 2006; Cook et al. 2010; Larson et al. 2010). It remains unclear whether bulk-scale samples are isotopically distinct when compared to micro-scale samples in field-based investigations. Had the mixed facies containing both the clear and herringbone crystal structures been sampled to determine the isotopic signature of the herringbone facies, the isotopic resolution would have been lost. This is shown through the mean isotopic differences between the mixed and herringbone facies which were -12.2‰ to -14.6‰ for δD and -1.9 to -2.3‰ for $\delta^{18}O$ (Table 3). This indicates that a micro-scale sampling approach has yielded a more accurate isotopic signature for the facies formed from supercooled water, rather than a bulk-scale sampling approach containing numerous facies.

Ice frozen from supercooled water at glaciers has been shown to be isotopically lighter relative to the vent water (Lawson et al. 1998; Ensminger et al. 2001; Cook et al. 2010; Larson et al. 2010). However, in our experiments the herringbone facies frozen from supercooled water was isotopically heavier relative to the initial reservoir and surrounding facies (Figure 4). These results are not the norm with regards to isotopic enrichment seen in stratified basal ice facies, anchor and frazil ice produced by supercooling. In our experiments, the clear ice formed at the beginning of the system, whereas the herringbone ice formed during the latter stages. Souchez and Jouzel (1984) assert that ice which forms at the beginning of a system will be isotopically lighter, whereas ice which forms last will be isotopically heavier, relative to the initial water. Experiment 1 had a freezing slope of 7.23, yet the clear facies had a slope of 6.33, the herringbone facies a slope of 6.15 and the mixed ice 3.96. Souchez and De Groote (1985) stated ice facies that form in a closed-system should have similar slopes to that of the system because there is no mixing of external water sources. Despite the closed-system experiments here, the facies have contrasting slopes. This could be because the initial reservoir became isotopically heavier throughout the seven-day period and the facies which froze at different periods of the experiments had different slopes. As the clear facies formed at the start of the experiment when the initial reservoir was relatively isotopically light. The herringbone facies formed in the latter stages of the experiment when the water was isotopically heavier, compared to the water that formed the clear ice at the start of the experiment. Thus, the isotopically heavy nature of the herringbone ice can be explained by a Rayleigh fractionation process. Despite the facies frozen from supercooled water not experiencing similar isotopic enrichment as seen in field-based investigations, our results confirm the importance of sampling size in correctly distinguishing the facies diagnostic of supercooling.

The statistical difference between the facies is because of the mixed facies containing two separate crystal structures with contrasting isotopic compositions. We suggest the mixed ice isotopic composition is being amalgamated because of the light isotopic composition of the clear ice and the heavy isotopic composition from the herringbone ice. This emphasises the need for a micro-scale sampling approach and removal of alternate ice facies in a believed ‘supercooled’ sample. Consequently, the assertions of Cook et al. (2010) that sample sizes of basal ice will be important for isotopic analysis as bulk-scale sampling could be homogenising isotopic signatures are correct in the case of this study.

Despite the aim of our study being to determine the potential difference between the mixed and herringbone ice facies, it is also important to note that there is a significant statistical difference between the clear and mixed facies. This suggests that the mixed facies cannot distinguish a precise isotopic composition for both the clear and herringbone facies, instead exhibiting a distinct isotopic signature. This supports the concept that bulk-scale sampling techniques could be amalgamating isotopic compositions from contrasting facies and a micro-scale approach is worth considering to ensure more precise measurements.

4.2 Isotopic Analysis

Our results indicate that the closed-system model by Jouzel and Souchez (1982) did not align with the actual freezing slopes of our experiments (Table 3), suggesting a complex freezing system. Had the model determined the correct freezing slope, it would have suggested the water froze from simple freezing. Sharp et al. (1994) found basal ice facies at Variegated Glacier, Alaska had formed from a different water source or the stratified facies had been subject to modification post-formation. This was concluded because the closed-system model calculated slopes of 6.37 and 6.64 for two initial liquids, which did not correlate with the actual slope of 5.77 (Sharp et al. 1994). Fitzsimons et al. (2008) determined an overriding apron at the Victoria Upper Glacier, Antarctica did not form the basal ice because it was isotopically distinct, with a predicted freezing slope of 5.6 which was not significantly similar to the actual slope of 6.6. Gordon et al. (1988) found the actual freezing slope at Flute's Glacier, Norway had a gradient of 5.5 which was in close agreement with the closed-system model which calculated a slope of 5.7, therefore basal ice formed from a melting-refreezing process.

4.2.1 Initial Water Differences

The Jouzel and Souchez (1982) model and the coefficients by Lehmann and Siegenthaler (1991) were formulated based upon meteoric water, yet our study utilised tap water. This mismatch in parent water could be the controlling parameter for the failure of the models predicting the freezing slopes of the experiments. For example, the isotopic composition of the tap water varied throughout the experimental period, resulting in different experiments having different parent waters. Experiment 1's parent water had an isotopic composition of -49.87‰ for δD and -7.674‰ for $\delta^{18}O$, whereas experiment 4's composition was -50.12‰ for δD and -6.060‰ for $\delta^{18}O$. If the models cannot be applied to a tap water source, other explanations of a complex freezing system will be of secondary importance. This has presented a potential avenue for further work to determine whether Jouzel and Souchez (1982) closed-system model can be applicable for different water sources, other than meteoric.

4.2.2 Potential Kinetic Isotope Effects

The deuterium excess-δD diagram (Figure 5) demonstrates the facies isotopic values tend to become heavier with progressive freezing through the closed-system. Souchez et al. (2000) found δ-values decreased towards the base of the ice cover, suggesting the downward movement of a freezing front. Our results indicate similar findings as our system froze progressively downwards and consequently resulted in the heaviest deuterium excess values contained in the herringbone facies as it was the last to freeze. Yde et al. (2010) studied basal ice facies at Russell Glacier and found that apart from the white ice, the other ice types had deuterium excess values between 2.0 and 4.2, suggesting there was no evident correlation with δD. It was inferred that the basal ice facies had been affected by; 1) kinetic parameters; 2) the local meteoric water had an average deuterium excess value within the range; 3) partial freezing or 4) variations in parent waters (Yde et al. 2010). Our results do see an inverse fractionation process. This occurs when the isotopes which are substituted are stably bonded during the transitional period and the molecules containing the heavy isotopes react quickly (Casciotti, 2009). Our experimental method could have caused the water isotopes in the facies to be stably bonded during transitional and progressive freezing of a downward front, resulting in an inverse fractionation process.

4.3 Basal Ice Context

We are aware that our experiments are laboratory based and do not perfectly replicate real-world conditions. However, our results highlight the importance of the scale of sample of basal ice collected for isotopic analysis. There have long been questions regarding the importance of sample sizes of basal ice for isotopic analysis (Souchez et al. 1998; Hubbard and Sharp. 1993; Cook et al. 2010). Hubbard and Sharp (1993) demonstrated that a bulk-scale sampling approach could incorporate different laminae of facies and may not allow a high enough resolution for a particular basal ice layer which has formed from a singular freezing event. Consequently, the overall benefit of a high-resolution sampling approach is more accurate isotopic signatures of basal ice layers in question. If a sample amalgamates different facies formed from different initial waters and formational processes, the isotopic resolution of the wanted basal ice layer will be lost, as presented here. If the mixed facies in our experiments were used as the only proxy for a supercooled formation, the diagnosis would have been misleading and fundamentally inaccurate. This theory could be applied to basal ice studies in general because of the complexities of stable water isotope analysis at glaciers. We have provided a proof of concept experiment for all basal ice investigations to consider the scale of samples for isotopic analysis. Further work is needed in basal investigations at glaciers to determine whether our theory is correct and will hopefully develop our understanding of sample size resolution in the real-world.

5.0 Conclusions

We have four overarching conclusions;

1) Our study concludes with confidence that previous bulk-scale sampling approaches could have overlooked important isotopic differences in ice formed from glaciohydraulic supercooling.
2) Studies should consider their sample sizes of stratified basal ice, as a micro-scale approach could yield much more accurate and detailed isotopic compositions of basal ice frozen from supercooled water.
3) Our results lend support to Cook et al. (2010), suggesting that bulk-scale sampling techniques could be homogenising the isotopic signatures of formational processes.
4) The results express the clear need for future research investigating glaciohydraulic supercooling to determine whether similar results are found at a micro-scale in basal ice investigations at glaciers.

If basal ice investigations revised their sampling strategy to a more micro-scale approach, we could see more detailed isotopic signatures for ice formed from supercooled water and would further advance our understanding of this important subglacial process.

The freezing slopes identified in our four experiments were not predicted by the model of Jouzel and Souchez (1982). We conclude that this was due to two factors; 1) the system underwent a complex freezing process over the seven-day experiment and 2) the use of tap water rather than meteoric water as the parent water source.

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Declaration of interest statement

In accordance with Taylor & Francis policy and our ethical obligation as researchers, we report having received no funding and declare that none of the authors have a conflict of interest.

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Appendices

A1. Isotopic compositions of the ice facies presented in this study.

Sample	δD (‰)	$\delta^{18}O$ (‰)
Parent (experiment 1)	-49.87	-7.67
Parent (experiment 2)	-50.31	-7.44
Parent (experiment 3)	-50.12	-6.06
Parent (experiment 4)	-49.75	-6.06
Experiment 1		
Herringbone	-81.79	-12.21
Herringbone	-77.63	-11.51
Herringbone	-75.72	-11.31
Herringbone	-77.46	-11.21
Herringbone	-71.62	-10.67
Herringbone	-75.96	-11.22
Herringbone	-70.74	-10.34
Mixed	-60.50	-8.76
Mixed	-59.64	-8.66
Mixed	-63.97	-9.45
Mixed	-61.44	-9.53
Mixed	-63.23	-9.66
Mixed	-65.84	-10.24
Mixed	-59.01	-9.00
Clear	-44.15	-6.92
Clear	-44.01	-6.73
Clear	-39.64	-6.52
Clear	-37.51	-5.85
Clear	-43.50	-6.74
Clear	-48.27	-7.59
Clear	-44.67	-7.01

Experiment 2		
Herringbone	-73.34	-10.89
Herringbone	-67.81	-9.95
Herringbone	-80.95	-11.92
Herringbone	-84.15	-12.42
Herringbone	-87.71	-12.82
Herringbone	-73.79	-10.80
Herringbone	-76.76	-11.23
Mixed	-70.06	-10.17
Mixed	-56.31	-8.16
Mixed	-60.53	-8.75
Mixed	-63.90	-9.16
Mixed	-67.70	-9.74
Mixed	-73.37	-10.40
Mixed	-67.71	-9.63
Clear	-44.19	-6.32
Clear	-35.99	-5.27
Clear	-33.09	-4.83
Clear	-46.38	-7.34
Clear	-33.44	-5.46
Clear	-32.58	-5.39
Clear	-46.28	-7.28
Experiment 3		
Herringbone	-77.67	-10.96
Herringbone	-68.54	-10.27
Herringbone	-68.88	-9.63
Herringbone	-80.42	-11.67
Herringbone	-86.48	-12.67
Herringbone	-72.04	-11.00

Herringbone	-78.05	-11.54
Mixed	-65.10	-9.63
Mixed	-60.21	-7.77
Mixed	-58.48	-8.20
Mixed	-59.34	-8.93
Mixed	-67.11	-9.84
Mixed	-57.60	-7.81
Mixed	-62.37	-9.41
Clear	-54.31	-6.94
Clear	-55.40	-8.16
Clear	-55.74	-8.02
Clear	-46.20	-5.49
Clear	-41.86	-5.53
Clear	-40.04	-6.39
Clear	-43.17	-6.77
Experiment 4		
Herringbone	-71.70	-9.84
Herringbone	-83.91	-13.52
Herringbone	-71.93	-10.86
Herringbone	-62.32	-10.00
Herringbone	-84.37	-12.95
Herringbone	-73.40	-11.96
Herringbone	-84.64	-13.66
Mixed	-62.81	-10.43
Mixed	-63.37	-10.53
Mixed	-68.09	-10.13
Mixed	-61.89	-9.07
Mixed	-67.26	-9.70
Mixed	-60.48	-8.15

Mixed	-62.97	-8.59
Clear	-34.32	-4.04
Clear	-39.42	-4.44
Clear	-37.21	-3.78
Clear	-34.74	-3.41
Clear	-37.35	-3.46
Clear	-43.72	-6.04
Clear	-43.30	-6.01