Correspondence

Laboratory observations of debris-bearing ice facies frozen from supercooled water

Seminal papers in this journal (Alley and others, 1998; Lawson and others, 1998) initiated a continuing debate about the role of glaciohydraulic supercooling in glacial sediment transfer and glacier dynamics. Supercooling has been invoked to explain anomalously thick basal ice sequences beneath temperate glaciers, relationships between glacier dynamics and subglacial erosion, and even the debris content of North Atlantic Heinrich layers. However, the application of supercooling theory to the problem of basal ice formation remains controversial. Proponents of the theory argue that subglacial accretion of ice and debris is almost inevitable where the physical conditions are conducive to supercooling, and that thick basal ice sequences (or evidence of them in the sedimentary record) can serve as evidence of supercooling. By contrast, others argue that supercooling is not the only mechanism for producing thick basal ice sequences at temperate glaciers, and that it is premature to use data from basal ice or glacial sediments as a tool for reconstructing the supercooling process or inferring that supercooling has occurred.

A key problem is to distinguish reliably between basal ice formed by supercooling and basal ice formed by other processes. At sites where supercooling occurs in southern Iceland, for example, Roberts and others (2002) cited crystallographic and sedimentological similarities between ice forming in supercooled subglacial water and ice in the basal layer as evidence of a process–form relationship between supercooling and basal ice, but other studies failed to identify any such similarity or relationship (e.g. Spedding and Evans, 2002; Cook and others, 2005). Even where supercooling of subglacial water can be demonstrated, and where the formation of basal ice from freezing of supercooled water might therefore be anticipated, we lack diagnostic criteria by which we can reliably associate specific basal ice facies to the supercooling process. Tritium content in ice, which has previously been cited as corroborating evidence of supercooling, indicates the age or provenance of the parent water but not the mechanism of freezing. Stable isotope analysis can indicate a freezing origin, but not whether the freezing was associated with supercooling. To attribute basal ice reliably to a supercooling origin thus remains difficult.

Two approaches might assist in resolving this difficulty, and our aim is to highlight opportunities for progress in this area. One approach is the characterization of (i) ice forming in supercooled water emerging from beneath the glacier, (ii) ice within the basal layer at glaciers where supercooling occurs and (iii) ice within the basal layer at non-supercooling locations, to clarify whether any diagnostic characteristics can be uniquely associated with basal ice derived from supercooling. Some progress has already been made here (e.g. Evenson and others, 1999), but reliable discrimination between basal ice facies of supercooled and non-supercooled origin remains elusive. A second approach, upon which we have embarked, is to use laboratory simulation to identify the crystallographic, sedimentological and chemical characteristics that should be expected of basal ice created by freezing turbid supercooled water.

In our experiments we have created ice from turbid water by two methods: (i) by reducing the ambient temperature and (ii) by supercooling the water before then raising the freezing point. These two approaches, supercooling and non-supercooling, produce different ice facies, with distinctive physical and chemical characteristics, at each stage of freezing. This provides a template by which to distinguish in the field between ice frozen by temperature change (for example water flowing from warm to cold thermal regimes at the glacier bed) and ice frozen by freezing-point change (for example through processes associated with glaciohydraulic supercooling).

Supercooling was achieved and controlled by varying the turbulence of the water. In early pilot studies using sediment-free water we employed both turbulence-controlled supercooling and pressure-controlled supercooling, and found no difference between the experimental results. The turbulence method was adopted because it had the additional advantage of keeping sediment within the water in suspension in a manner broadly analogous to the subglacial prototype. Turbulence was maintained by a Tecam TE-7 Tempette bath-recirculating pump clamped to the rim of the tub. To provide a framework for comparison we ran parallel experiments with turbulent water and still water, and at different ambient temperatures. The water was loaded with 200 cm^3 each of clay, silt and fine sand. The procedure for all experiments started with cooling water in 100-litre tubs placed in a pre-chilled cold room at temperatures ranging from –2 to –20°C. The still water was cooled past its freezing point and allowed to freeze. The turbulent water reached a lower temperature before starting to freeze, at which point we followed two parallel approaches. In ‘supercooling’ experiments turbulence was switched off, causing the freezing point to rise and the now supercooled water to freeze. In ‘progressive cooling’ experiments we maintained turbulence, allowing the water to freeze only as the water temperature dropped further.

Our experiments produced three physically distinctive ice facies associated with different styles and stages of freezing, each corresponding to basal ice facies that have been observed in the field.

1. Freezing of supercooled water by raising the freezing point (by a reduction in either pressure or turbulence) can produce ice with a distinctive herringbone structure of interlocking crystals marked by intracrystalline bubble- and debris-lineations (Fig. 1). We have been able to create this ice type only by raising the freezing temperature of supercooled water, and never by cooling water past the freezing point, suggesting that this facies may be diagnostic of supercooling. A similar ice facies has also been observed at Icelandic glaciers (Cook and others, 2005).

2. Unidirectional freezing of turbulent turbid water under progressive cooling conditions with an unvarying freezing temperature can result in creation of clear ice containing silt pellets (Fig. 2), similar to dispersed facies ice described from many glaciers (Knight, 1997). This facies was created in our experiments without any supercooling, and is thus not a valid indicator of supercooling in the field. Likewise, these observations suggest that silt pellets within glacial sediments are not

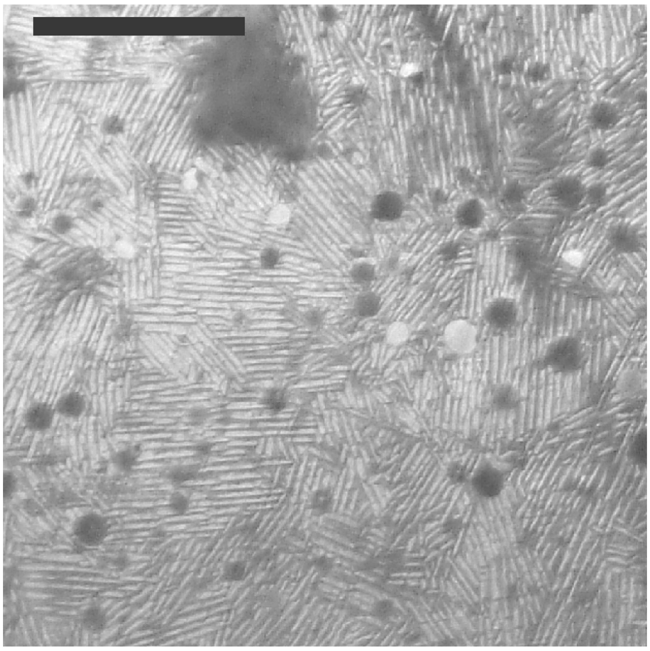

Fig. 1. Distinctive 'herringbone' ice, formed only by freezing supercooled water. Scale bar = 1 cm.

reliable indicators of supercooling beneath former glaciers, as has previously been suggested (e.g. Larson and others, 2003).

3. Both reducing water temperature to the freezing point, and raising the freezing point to the temperature of supercooled water, can produce frazil ice crystals within the water, which can aggregate into masses similar to the frazil floc and anchor ice described by Evenson and others (1999), trapping sediment between the crystals (Fig. 3). Frazil ice and associated facies are therefore not necessarily diagnostic of supercooling.

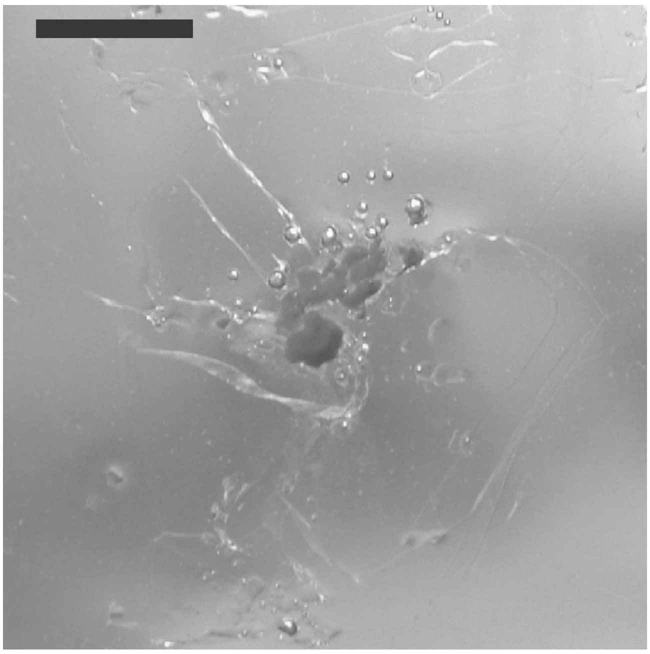

Fig. 2. Ice with included silt pellets, formed by directional freezing of cooling (not supercooled) turbid water. Scale bar = 1 cm.

Fig. 3. Agglomeration of frazil and needle ice, formed by freezing both from supercooled and from progressively cooling water. Scale bar = 1 cm.

Our experiments have also indicated that the different freezing processes can produce distinctive chemical signatures in the ice as a result of solute fractionation during the freezing process. Directional freezing caused by progressive cooling and penetration of a freezing front results in the expulsion of dissolved impurities and their concentration in the unfrozen fraction. Frazil ice and clear ice produced in our experiments were solute poor relative to the parent water and were associated with a solute-enhanced unfrozen fraction at the end of partial-freezing experiments. By contrast, freezing of supercooled water results in multidirectional crystal growth, incorporation of solutes within the ice, and a reduced solute concentration in the unfrozen fraction (Fig. 4). Our early experiments indicate that it is not the rate but the geometry of freezing that controls solute incorporation within ice facies forming from supercooled water. These observations suggest a way forward, using

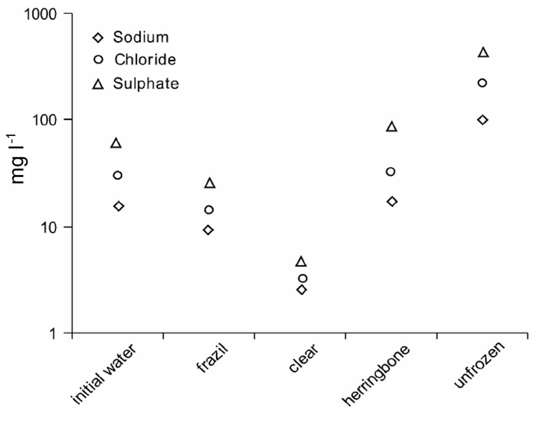

Fig. 4. Solute concentration in parent water, and in the frazil, clear and herringbone ice facies and residual water after experimental freezing.[AUTHOR: Should it add whether water is supercooled for clarity?]

chemical signatures of both ice and unfrozen subglacial water to identify basal ice formation by supercooling.

Glaciohydraulic supercooling is an important process with great significance for glacier dynamics and glacial geology. However, we fear that over-enthusiasm in attributing characteristics of basal ice or glacial sediments to supercooling, using diagnostic methods that have not yet been demonstrated to be thoroughly reliable, could lead to misinterpretations of glacial and geological signatures. We call for further debate about diagnostic signatures of supercooling and greater caution in inferring supercooling from the characteristics of basal ice and glacial sediments.

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