3.4.1. Sampling and describing glacier ice

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ABSTRACT: Determination of the physical, chemical and biological properties of glacier ice is essential for many aspects of glaciology and glacial geomorphology. In this chapter, we draw principally on examples of the description and sampling of the basal zone of glaciers where the ice is in direct contact with its substrate, and hence is where a great deal of geomorphological work is achieved. Whilst a pre-determined sampling strategy is essential to inform sampling equipment requirements, flexibility in data collection is necessary because of the dynamic nature of glaciers, and variability of ice exposure. Ice description is best achieved through stratigraphic logging, section drawing and photography. Detailed description can include a variety of information about the nature of layering, structures and sediment distribution; the size, shape and roundness of included debris; ice crystallography; and bubble content. It is common practice to categorise descriptively different ice types into cryofacies, so that comparisons can be made between studies. Sample extraction may be required for more detailed analyses of the physical, chemical and microbiological composition of the ice. We outline the use of a number of tools for ice sample extraction, including chainsaws, ice axes, chisels and ice screws.

KEYWORDS: cryofacies, glacial sediment, ice crystallography, sampling, stratigraphy

Introduction

Glaciers are highly heterogeneous in nature, comprising a wide variety of ice types with different characteristics. Traditionally, glaciologists and geomorphologists have focused on characterizing the physical and chemical nature of glacier and basal ice (e.g. Hubbard and Sharp, 1989; Knight, 1997), although increasingly, biological characteristics are being considered (e.g. Hodson et al., 2008; Montross et al., 2014).

The diversity and complexity of ice types result from factors including flow and strain histories within the glacier; the character of parent snow, ice or water, as well as entrained sediment; sediment availability and processes of entrainment; melting and re-freezing; and many more (Hubbard and Sharp, 1989; Knight, 1997). Accounting for differences in ice composition is important. For example, ice characteristics (e.g. sediment content, structure, presence of chemical impurities) affect its rheological properties, and hence impact upon ice flow (e.g. Fitzsimons, 2006; Chandler et al., 2008). Equally, the origin and history of the ice can be interpreted from its physical characteristics (e.g. Knight, 1997; Hambrey and Lawson, 2000; Cook et al., 2010, 2011a; Lovell et al., 2015).

For the most part, glacial geomorphologists are interested in the amounts of geomorphological activity (i.e. erosion and sediment transfer) achieved by glaciers (e.g. Hallet et al., 1996), and the deposition of sediment to create landforms and sediments, such as moraines and till (e.g. Cook et al., 2011b). Increasingly, however, there is recognition of the role of glaciers in global biogeochemical cycles (especially carbon), and the discharge of carbon and other nutrients to downstream ecosystems (e.g. Hood et al., 2015). Hence, there is a need to describe, sample and classify the different ice types that exist within glaciers. In this chapter, we outline how this is achieved, focusing on the basal zone of glaciers where
the glacier interacts directly with its substrate, which is of most relevance to geomorphologists.

Selecting locations for ice description and sampling

The fundamental issue facing most researchers is what to describe and sample. As with any study, a carefully designed sampling strategy is important in order not to bias results, and the exact approach will depend on the purpose of the study. The dynamic nature of glaciers can make planned sampling strategies difficult to apply. For example, some cryofacies (i.e. distinct ice types) may be visible on some field visits and not on others, and safe access to sampling locations is always a consideration and limitation. Nonetheless, it is useful to have a sample ‘wish list’ before leaving for fieldwork (particularly, to inform equipment requirements) but flexibility is often necessary depending on what is visible and accessible in the field. It is also worthwhile consulting recent satellite imagery (e.g. most recent Google Earth or Landsat imagery) before fieldwork to plan access to the glacier margin and surface. Once in the field, it is worthwhile devoting time (perhaps a few days) to reconnoitering the glacier margin, identifying suitable sampling locations and practicing sampling before embarking on the sampling campaign itself.

Describing and classifying ice

In most cases, the description and sampling of ice are undertaken together in the field, starting with description. Once a suitable location has been selected, it is good practice to document the nature of the site prior to sampling, which usually requires the removal of large quantities of ice and sediment. Take field sketches, photographs (using reference objects, such as ice axes or people, for scale) and any basic measurements (e.g. height) of the undisturbed ice section or surface. Basal ice exposures are commonly covered by a surficial smear of sediment, and it may be necessary to clean the section (e.g. by sluicing it with meltwater) before logging and photographing to reveal ice types more clearly (Figure 1).

Figure 1: (a) Cleaning an ice section by sluicing with meltwater. (b) Example of basal ice section that has been cleaned by sluicing. Note how different ice types (a lower layered ice type and an upper coarse, white ice type) are clearer in the cleaned section compared to the non-cleaned sections either side.

The process of stratigraphic logging starts with the identification of the cryofacies present within the section, which in turn requires ice description. A cryofacies, in the context of the cryospheric sciences, is ice that has a suite of characteristics that enable it to be distinguished from other ice types (e.g. Hubbard et al., 2009).

Several physical characteristics can be explored when producing a stratigraphic log or section diagram, and these characteristics are often used to classify ice into constituent cryofacies (e.g. Lawson, 1979; Hubbard et al., 2009). Examples of visually different cryofacies are shown in Figure 2 and give some impression of how variable basal
cryofacies can be. The characteristics recorded in basal ice stratigraphic logs are in many ways similar to those recorded for studies in sedimentary geology (e.g. Nichols, 2009; Miall, 2016), and include:

- ice layer thickness
- nature of contacts between layers (sharp, gradational, unconformable, etc.)
- horizontal extent of the layer (e.g. whether it is continuous, or pinches-out laterally)
- evidence for tectonism or deformation (e.g. folds, faults, boudins)
- sediment content (as volumetric or gravimetric percentage of sediment in the ice)
- sediment distribution (e.g. solid sediment with interstitial ice, random distribution of clasts or sediment aggregates within an ice matrix, bands of clasts or aggregates)
- nature of the entrained sediment (estimated particle size, lithology, shape and roundness of particles, etc.)
- ice crystal size
- bubble content, size and shape (e.g. spherical, elongate).

Whilst many physical characteristics can be estimated visually, further quantification of some properties is possible either in the field, or at a field base or camp. Ice crystal size can often be estimated and measured where ice surface melting accentuates the vein network between crystals. However, measurements can also be made by progressively thinning a small piece of ice on a hot pan lid, heated on a field stove. Once the ice is ~1 mm thick, it can be placed between polarizing filters, held to the light and photographed, ideally with a scale in the image (Figure 3). Measurements of ice crystal size can then be made on a computer screen at a later date using image analysis software.

Debris volume measurements can be made by returning bagged samples to the field base, allowing them to melt, decanting them into measuring cylinders, and waiting for the sediment to settle, which can take variable amounts of time from hours to days depending on the grain size. In addition, in the case of very fine-grained sediment,
centrifuging samples could be necessary to force the deposition of colloidal-sized suspended sediment. The volume of sediment and water can be measured directly in the cylinder, but it is important to consider the density difference between water and ice; any water volume should be multiplied by 0.9 to allow calculation of the percentage volume of sediment in ice.

Figure 3: Example of a thin section of ice viewed through polarizing filters. (Photo: N. Midgley).

Clast shape, roundness and fabric analyses can also be conducted in the field (e.g. Benn, 2004). Typically, between 30 and 50 clasts per sample would be extracted for these analyses, although this can be particularly time-consuming when clasts must first be removed from the ice with an ice axe or chisel.

Once the ice has been described, it is common to develop a cryofacies classification or naming scheme, or to use a pre-existing classification scheme. The classification of glacier basal ice into distinct cryofacies was first applied by Lawson (1979) at the Matanuska Glacier, Alaska. However, since then, a range of individual classification schemes have been devised for individual studies or glaciers (e.g. Knight, 1987; Sharp et al., 1994; Hubbard and Sharp, 1995; Christoffersen et al., 2006; Cook et al., 2007), which has led to the proliferation of multiple names for descriptively similar cryofacies. This confusing situation has led to attempts to unify existing basal ice facies classification schemes (e.g. Knight, 1994; Hubbard et al., 2009). Given that basal glacier ice and permafrost are essentially the same materials (a mix of ice and sediment), Waller et al. (2009) recommended greater collaboration between glaciologists and permafrost scientists who have been using permafrost classification schemes successfully for some decades (e.g. Murton and French, 1994; French and Shur, 2010). This remains a promising prospect, but has yet to be applied more widely.

The most recent attempt to develop a unified, non-genetic scheme for classifying and naming basal cryofacies was undertaken by Hubbard et al. (2009). Their scheme was based principally on the nature of layering and distribution of included sediment. The scheme comprises six primary cryofacies and twelve composite cryofacies (Table 1). Figure 4 illustrates a flow chart of how to classify and name basal cryofacies according to this scheme.

Overall, we recommend either using a unified classification scheme, such as that of Hubbard et al. (2009) or, where researchers prefer to develop their own schemes, that comparisons be drawn with cryofacies descriptions in existing studies so that broad similarities and differences can be drawn out between glaciers. Certainly, it would be worth pursuing the suggestion of Waller et al. (2009) for closer ties between glacial and permafrost researchers, and the development of common practices between these two sub-disciplines of cryospheric science.

Once described in the field, the documentation of the presence of cryofacies is best achieved through stratigraphic logging, section drawing, or both. Stratigraphic logging involves determining the thickness of layers within a cleaned section, the nature of each of those layers (as discussed above), and the nature of the contacts between individual layers (e.g. sharp, gradational, etc.). An introduction to stratigraphic logging can be found in Evans and Benn (2004). A measuring tape is usually fixed vertically up the cleaned section to provide a reference scale from which to log. Similar principles can be applied on the glacier surface where, for example, there may be layering and changes in ice types and structures along a transect.
Table 1: Basal cryofacies classification and naming scheme of Hubbard et al. (2009).

<table>
<thead>
<tr>
<th>Layered</th>
<th>Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typical thickness of primary component layers</strong></td>
<td><strong>Typical debris concentration of basal cryofacies</strong></td>
</tr>
<tr>
<td>Metres or longer</td>
<td>Centimetres to decimetres</td>
</tr>
</tbody>
</table>

**Predominantly layered**

<table>
<thead>
<tr>
<th>Stratified (St)</th>
<th>Banded (B)</th>
<th>Laminated (L)</th>
<th>Solid (So)</th>
<th>Dispersed (D)</th>
<th>Clean (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratified solid (StSo)</td>
<td>Banded solid (BSo)</td>
<td>Laminated solid (LSo)</td>
<td>Solid stratified (SoSt)</td>
<td>Dispersed stratified (DSt)</td>
<td></td>
</tr>
<tr>
<td>Stratified dispersed (StD)</td>
<td>Banded dispersed (BD)</td>
<td>Laminated dispersed (LD)</td>
<td>Solid banded (SoB)</td>
<td>Dispersed banded (DB)</td>
<td></td>
</tr>
<tr>
<td>Solid laminated (SoL)</td>
<td>Dispersed laminated (DL)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Predominantly uniform**

![Flow-chart illustrating how to name and classify basal cryofacies](re-drawn from Hubbard et al., 2009).
Sampling ice

Once the ice has been described and logged, consideration should be given to representative sampling. It is common to extract target samples for a variety of further analyses in the field and laboratory such as quantification of debris content, particle size analysis of included sediment, ice crystal size and fabric, geochemistry, stable isotope composition, and cell concentration and extraction of DNA for microbiological studies. The purpose of the analysis will determine the extraction process, since extra care must be taken for some sensitive analytical techniques (e.g. chemical or biological) in order to avoid cross-contamination. Before ice samples are extracted, it is important to remove any ice that may be contaminated with surface water or debris. This is particularly important at the glacier margin and surface of the ablation zone, where several decimetres thickness of ice may be affected by the penetration of surface water and sediment migrating along fractures and intra-crystalline veins. In most cases, removal of the top 20-30 cm of surface ice with an ice axe is sufficient to avoid surface contamination issues.

The choice of tool for ice sample extraction depends on the size of sample required, the nature of the ice being extracted, the need for aseptic microbiological sampling, and the availability of equipment. Where large ice samples are required (e.g. for return of decimetre-size ice blocks to a laboratory for crystal fabric analysis), or for the opening of a channel or tunnel, a chain saw may be the most effective tool (e.g. Fitzsimons et al., 1999; Hubbard and Glasser, 2005). However, as Hubbard and Glasser (2005) note, chainsaw injuries can be extremely serious, and fieldwork is often undertaken far from medical facilities. Hence, extreme care should be taken, and the operator should be trained and properly equipped (i.e. with hardhat, visor or goggles, ear defenders, protective gloves, protective trousers and protective boots) (Hubbard and Glasser, 2005). Other issues include the rapid wearing of chainsaw teeth when cutting through sediment-rich ice, and that chainsaw blades can freeze solid into ice sections at very cold temperatures if left for even relatively short periods of time.

Perhaps the most common tool used for ice sample extraction is the ice axe (Figure 5a). For more precise sample removal, it may be better to use a hammer (or cobble) and chisel (Figure 5b) once the unwanted surface ice has been removed using an ice axe. For even greater precision, and usually much smaller samples, an ice screw can be used (Figure 5c), although for very debris-rich ice or for ice containing clasts, this can be ineffective.

Figure 5: Ice sampling techniques using (a) an ice axe; (b) a chisel; and (c) an ice screw.
Whichever extraction technique is used, it is important to consider contamination issues. For samples that are used to characterize the physical composition of the ice (e.g. sediment content, ice crystal size, bubble content), it is reasonable to expect that surface contamination will have been diluted significantly or completely by the point where the rotten surface ice has been removed. Hence, the same tool can continue to be used to extract the sample. To be certain of low contamination, a different, clean tool could be used for the final sample extraction. For ice geochemistry or microbiology samples, it is desirable to minimise contamination by using clean, sterile equipment. If microbiological samples are being collected, then metal sampling implements should be cleaned and ideally sterilized, typically achieved by flaming with the aid of ethanol (e.g. Skidmore et al., 2005). Note, however, that it is impractical to keep tools sterile during sampling, because the tool will be used to penetrate contaminated surface layers. It is therefore necessary to work in a planned way that does not rely on tool sterility for maintaining sample integrity. Laboratory or medical gloves are useful for minimizing the introduction of salt from sweat, or of microorganisms from skin. For high sensitivity chemical and microbiological applications a useful technique is to chip ice fragments directly into a sample bag without touching by hand or tool. This can be achieved by chiseling extensively around the feature of interest until it can be released by fracturing the back of the sample, ideally with a single chisel blow. Whilst delivering the releasing blow, a sample bag is held firmly inside-out over the feature by an assistant who captures the sample.

It is vital that sample bags and vessels be labelled clearly with a permanent marker and, where samples are to be transported back to a laboratory, it is advised that the sample name be labelled in several locations on the bag or vessel as labels can wear off in transit. Aside from the sample name, it is advised that, space permitting, other useful information, such as GPS coordinates, sample type (e.g. cryofacies), and individual identifying code be recorded on the bag and vessel, as well as in a field notebook. Remember also to mark on the section diagram or log where the sample was taken, and take a photograph. To avoid cross-contamination and sample loss due to leakage, it is worthwhile double- or triple-bagging the ice samples, since ice can have sharp edges capable of piercing bags.

Several laboratory data analysis techniques require separation of solid and liquid components of the samples, or may require the sample to be returned frozen (e.g. sediment particle size analysis, stable isotope analysis, etc.). Filtering of samples can be achieved easily in a field base or camp. The simplest set-up is the use of filter papers in a funnel to collect sediment (e.g. for laboratory particle size analysis). Perhaps the most effective technique is to use a vacuum pump such that both the sediment and clean water samples can be collected at the same time. Fine filters tend to clog easily with fine sediment, so this can be a time-consuming process for debris-rich samples. Water can be decanted from the collection chamber and bottled as required (e.g. in 8 ml Nalgene screw-cap bottles).

Concluding remarks

The description and sampling of ice is essential for many aspects of the cryospheric sciences. For example, documenting and measuring ice properties can provide vital information about the origin and geomorphological significance of cryofacies, the rheology of ice and its impact on glacier flow, and the potential for ice to serve as a microbial habitat. Much can be learned from visual description and classification of ice in the field, although ice samples are often required for more detailed physical, chemical and biological analyses. A carefully thought-out sampling strategy is important for the success of any campaign involving the description of ice and retrieval of ice samples, and is essential for estimating the appropriate type and amount of sampling equipment. However, the dynamic nature of ice margins and surfaces means that flexibility is required to account for access and safety issues.

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