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Sea ice crystal texture and microstructure

Introduction

The importance of the polar oceans' sea ice cover for global climate and polar ecology derives in significant part from the manner in which ice grows from seawater. Thus, sea ice contains large numbers of brine pockets, salt particles and other inclusions, typically ranging from few micrometers to several centimeters in size. The size, morphology and distribution of these inclusions and the surrounding ice crystal matrix is referred to as the texture or microstructure of the material. The remarkable properties of sea ice, such as its high albedo (ability to reflect light) or its role as a habitat to microorganisms thriving within the pore space, are determined in large part by its texture and microstructure.

The microstructure of a sea-ice sample also contains a record of ice growth conditions, and researchers have made use of this fact to learn more about the complex evolution of the ice cover. Such studies, employing a wide range of methods, from the traditional approach of cutting sections out of ice cores drilled in the field to non-destructive use of magnetic resonance imaging, can also offer more general insights into the formation and evolution of rocks and industrial materials at temperatures close to the melting point.

Major ice textures

In the Antarctic, four principal modes of sea-ice growth and formation can be distinguished. The different ice-growth processes result in different morphologies and spatial arrangements of ice crystals (or ice grains), air and brine pockets and other inclusions. Typically, ice crystals are several millimeters to >10 cm in size and the term *texture* is used here in accordance with the glaciological literature (Shumskii, 1964; Weeks and Ackley, 1986) to denote the size, shape and orientation of these crystals. The distribution of liquid and solid inclusions within the ice matrix as well as the morphology and substructure of individual crystals is denoted as the ice or pore *microstructure*. Note, that while modern geological literature tends to used the terms texture and microstructure synonymously (Passchier and Trouw, 1996), in the materials science field (and in some foreign languages, such as German or French) the terms may have different meanings. In describing and classifying different ice types based on crystal or pore attributes, it helps to distinguish between textural classifications that are purely descriptive of ice crystal texture (and possibly microstructure) and genetic classification schemes that distinguish between different formation modes as deduced from a number of different observations, including but not limited to the ice texture and microstructure (Figure 1).

During the onset of ice formation in open water, along the advancing marginal ice zone (*see also* Sea Ice Types and Formation) and within leads or polynyas (*see also* Polynyas, Leads in the Southern Ocean) wind-mixing typically results in the formation of frazil ice. Frazil crystals are mm- to cm-sized spicules or platelets of ice, not unlike a submarine type of snow, often aggregating into flocs as they collide in the upper meters of the water column. Eventually, the crystals accumulate at the ocean's surface and through further growth and deformation form grease or pancake ice (*see also* Sea Ice Types and Formation, Figure 1a-c). The rate of ice growth in the water column is typically limited by the rate at which the latent heat of fusion that is released during the congelation of seawater can be transferred to a heat sink, either the cold atmosphere or the supercooled ocean (i.e. at a temperature below the freezing point, typically at –1.9 ˚C; *see also* Surface Energy Balance). Frazil ice formation is typically associated with the highest rates of heat transfer. Hence, an unconsolidated, highly porous frazil layer of several decimeters thickness can easily be formed within a few hours under cold, windy conditions.

Once this surface grease ice layer dampens mixing in the water column to the extent that no further frazil formation is possible, it consolidates through freezing of seawater in the interstices between crystals. During this consolidation, salt is expelled from the ice. This expulsion is mostly driven by convective exchange, with dense, saline, cold brine overlying less dense, fresher and warmer brine (Figure 1), and to a lesser extent volume expansion of water during the freezing process. The ice formed through consolidation of frazil typically consists of isometric, small (few millimeters across) grains and is referred to as granular ice (Figure 2a). Individual grains are typically rounded (orbicular granular) and contain few if any inclusions. Brine is confined to the interstitial pore space. Due to the dynamic ice-growth environment of the Southern Ocean (*see also* Pack and Fast Ice; Sea Ice Types and Formation), granular ice of frazil origin is the most common type of ice found in the Antarctic, accounting for more than half of the total ice volume (Weeks and Ackley, 1986; Lange and Eicken, 1991; Jeffries et al., 1994; Worby and Massom, 1995; Eicken, 1998).

The quiescent accretion of sea ice at the bottom of an existing ice cover results in the formation of vertically elongated (prismatic) crystals, typically several centimeters in diameter and more than 10 cm long (Figure 1). This type of ice is referred to as columnar ice, or, based on its mode of formation, congelation ice. The downward growth of a floating sea-ice sheet is very similar to the growth of ordinary lake ice, and this is reflected in similar grain textures. Columnar sea-ice crystals, however, contain numerous layered brine inclusions, with seawater and brine trapped between ice lamellae protruding downward from the base of the ice sheet (Figure 1, 2b, 3). Vertically oriented ice lamellae possess a downward growth advantage, potentially enhanced by steady currents under the ice. This favours the growth of ice crystals composed of vertically oriented lamellae that are aligned within the horizontal plane if under-ice currents are consistently unidirectional (Figure 1).

In the Arctic, such strongly aligned columnar ice is the dominant ice textural type and accounts for roughly two thirds to three quarters of the total ice volume. Dynamic growth conditions in the Antarctic limit the occurrence of columnar ice to the lower-most layers of the ice cover, the landfast ice belt along the coast and within leads and polynyas that freeze over during calm conditions (wind speeds typically less than 5 to 10 m s^{-1}, Eicken and Lange, 1989; Smith et al., 1990). Furthermore, while vertically oriented columnar crystals are common, horizontal alignment is observedly only infrequently and generally both horizontal and vertical dimensions of columnar crystals in Antarctic sea ice (Figure 2b) are smaller than their Arctic counterparts.

The formation of so-called platelet ice, common along the margins of the Antarctic ice shelves where it can account for up to half of the ice volume, is similar in many ways to that of frazil ice. Thus, platelet ice results from the accumulation of large (several centimeters diameter), platy ice crystals in layers decimeters to on occasion meters thickness underneath the ice cover. Due to the larger size of voids enclosed by the platelets, the shapes and sizes of individual crystals within consolidated platelet ice span the range from granular to columnar ice (mixed columnar/granular ice, Figure 1, 2c).

Underwater ice platelets form during the ascent of supercooled water masses that have come into contact with the base of the floating ice shelves (Lewis and Perkin, 1986; *see also* Ice Shelves). The freezing point of seawater is both salinity and pressure dependent (approximately –1.92 ˚C at the surface for seawater of salinity 35, and –2.00 ˚C at 1000 m depth). As water circulates underneath an ice shelf it initially melts back the ice shelf base in deeper water, eventually cooling to the freezing point at depth. As the water rises along the sloping ice-shelf base, the pressure drops and supercooling with eventual ice formation sets in. Ice crystals grown under these conditions in the water column tend to be much larger (hand-sized plates have been found) than ordinary frazil ice and accumulate in thick layers underneath landfast and drifting sea ice in front of the ice shelves (Eicken and Lange, 1989, Smith et al., 2001). In some locations, such as McMurdo Sound, the supercooled water can make it all the way to the ocean surface without ice crystal formation, leading to direct accretion of platelet ice onto the existing ice cover.

The Antarctic sea-ice zone receives substantial snowfall, with low pressure systems transferring moisture from the surrounding ocean areas. In some regions it is possible to accumulate as much as 1 to 2 m of snow on the sea ice. The ice surface is depressed below sealevel as a result of snow loading. If the underlying layers are sufficiently permeable (with pathways provided by brine channels or cracks), the ice surface and snow base floods and eventually refreezes (Figure 1; *see also* Sea Ice Types and Formation). The snow ice formed in this fashion is composed of a mixture of frozen seawater, brine and snow crystals. Texturally, it is often difficult to distinguish from granular ice of frazil origin (such as shown in Figure 2). On occasion, ice grains in snow ice exhibit polygonal outlines in thin sections and are then referred to as polygonal granular ice.

Superimposed ice, formed from snow meltwater that percolates downward and refreezes at the cold ice surface in late spring and early summer, is also typically of polygonal granular texture. The contribution of snow to the mass budget of Antarctic sea ice can be significant; in some areas as much as half of the total ice mass can be composed of snow ice (Jeffries et al., 1994; Kawamura et al., 1997). In all but the most extreme cases (i.e., snow accumulation rates of several meters per year) the net effect of snow deposition on sea ice is a reduction in total ice volume due to its small thermal conductivity which is lower than that of sea ice by one order of magnitude. However, snow-ice and superimposed-ice formation help to significantly offset this reduction in ice mass from snow deposition. While large-scale modeling has made significant progress in simulating snow ice formation (Fichefet and Morales Maqueda, 1999; Wu et al., 1999), analysis of sea-ice cores (textural analysis and stable-isotope measurements) is the only means of directly determining the contribution of snow to the ice mass budget.

Pore microstructure

The ice crystal lattice structure does not allow for substantial incorporation of the major seasalt ions into the solid ice. Instead, salt is rejected and builds up ahead of the advancing ice-water interface during ice growth (Figure 1). Typically between 60 to 85 % of the total amount of salt is expelled completely from the growing ice in the form of cold dense brines. The remainder is trapped between and within the crystals. Salt build-up ahead of the ice-water interface is ultimately responsible for the development of parallel rows of ice blades that protrude from the bottom of growing columnar ice. Differences in the rate of salt and heat transport at the millimeter-scale result in a thin layer of supercooled water just below the ice. This supercooled water in turn fosters the establishment of a corrugated ice bottom: Ice lamellae shoot down into the supercooled layer and part of the brine remains trapped between the lamellae (Figure 2c, 3).

Traces of these ice blades and the interspersed brine layers can be discerned in the thin section photograph in Figure 2b. Figure 3, which has been obtained with the aid of magnetic resonance imaging (MRI) provides a close-up view of parallel arrays of inclusions within individual crystals. Along the boundaries of crystals with differently oriented inclusion arrays, slightly larger, cylindrical brine tubes are apparent (Figure 3a,b center). These tubes merge into systems of interconnected channels that can reach several centimeters in diameter and more than a meter in length.

Gas inclusions typically only account for a small fraction of the total volume of foreign inclusions in sea ice. Frazil ice formed in a turbulent upper ocean can trap air bubbles in the ice. Gas or vapour inclusions can also appear in brine channels as a result of temperature changes and displacement of dissolved gases from the growing ice (Light et al., 2003). Solid salts precipitate as the temperature of growing sea ice drops, with the two most prominent salts, mirabilite ($NaSO_4$ x 10 H_2O) and hydrohalite (NaCl x 2 H_2O) starting to precipitate as the temperature drops below approximately –6 and –22 ˚C, respectively (Marion and Farren, 1999).

Methods of studying sea ice microstructure

In principle, the methods employed in obtaining samples and analysing sea-ice microstructure and properties are very similar to those employed by glaciologists studying ice cores drilled deep into the Antarctic ice sheet (*see also* Ice-core analysis techniques). Ice cores are typically drilled with a fiberglass-barrel, motor-powered coring system (Figure 4a). With the use of extension rods, such corers can penetrate between 5 and 10 m of ice. In order to prevent loss of brine from the porous ice, cores are typically pre-cut at the sampling site after photographing and temperature measurements (Figure 4b), and then transferred to storage at temperatures of below –20 ˚C to prevent loss of brine. A standard variable determined on most cores in addition to temperature is the ice bulk salinity, which involves melting of the sample and subsequent electrolytical conductivity measurements. Other biogeochemical and stable-isotope measurements are typically also carried out on melted core sections.

The standard approach to textural and microstructural analysis involves the preparation of thin sections that can be examined with magnifying lenses or under the microscope in both ordinary and polarized light. Slices sawed off the core are frozen onto glass slides and subsequently thinned to few thenths of a millimeter in thickness. Placed between crossed polarizing sheets, these thin sections exhibit interference colors that indicate the shape and crystallographic orientation of individual ice crystals (Figure 2). The pore morphology can be studied at higher magnification in ordinary transmitted light. Since samples are typically prepared at low temperatures to avoid brine loss and alteration during processing, the pore microstructure is artificially changed as pores shrink and salts precipitate during the cooling process. This creates the dilemma that in order to insure overall sample integrity, standard core analysis is completed at artificially low temperatures, significantly altering pore microstructure. Many processes of scientific interest occur at higher temperatures, however. This has led to alternative approaches in studying ice microstructure, including x-ray computed tomography (CT; Kawamura, 1988) or magnetic resonance imaging (MRI; Menzel et al., 2000; Eicken et al., 2000; see also Figure 3). These methods derive their power from the fact that samples can be studied non-destructively by determining density contrasts (x-ray CT) or can distinguish between water molecules part of the solid ice or liquid brine (MRI). Furthermore, experiments conducted in closed sample vessels allow analyses of the thermal evolution of pore microstructure. The most advanced approach to the problems posed by thermal alterations of sea ice after sampling has been taken by a group in New Zealand who have pioneered *in situ* studies of brine volume and mobility of liquid water in sea ice using magnetic resonance techniques that rely on the Earth's magnetic field (Callaghan et al., 1999).

Microstructure and salt distribution and their impact on ice properties and ice ecology

The transport of energy and matter through sea ice is controlled by its texture and microstructure. This derives largely from the contrasting physical properties of ice (poor electrical conductor, good thermal conductor, mechanically strong) and brine (excellent electrical conductor, poor thermal conductor – although brine movement can under certain conditions enhance thermal transport, mechanically weak). The volume fraction of brine, the number density, morphology (tubular vs. layered) and connectivity of brine inclusions are of particular importance in this regard. While the growth mechanism and growth rate as well as the grain texture determine the bulk salinity, spatial arrangement of pores, their volume fraction, micromorphology and connectivity are mostly controlled by temperature. With decreasing temperatures, pores shrink and brine tubes or layers segregate into individual, disjoint pores as part of the liquid freezes out, leaving behind a colder, more saline brine. This segregation and reduction in connectivity of pores greatly reduces the ice permeability, which in turn significantly reduces fluid flow through the ice. Cold horizons of lower salinity, typically found just below the ice surface (Figure 1), can hence become effectively impermeable. This can prevent surface flooding in cold ice that is submerged below sealevel by a deep snow load. Once the ice interior and surface warm, however, ice permeability goes up and seawater and brine are free to percolate upward, resulting in formation of snow ice (Maksym and Jeffries, 2000). Such flooding processes explain higher salinities found in the lower layers of the snow cover. High surface sea-ice salinities are due to both potential flooding and higher retention of salts in the upper portions of the ice cover which experienced more rapid growth rates. Surface flooding is also of importance because it can supply large amounts of nutrients, allowing microalgae, which are prolific throughout the ice cover, to thrive in the uppermost layers where they are protected from grazers in the water column (Fritsen et al., 1998; *see also* Sea ice microbial communities and primary production).

Texture and microstructure figure prominently in the role of sea ice as a habitat for a wide range of microorganisms. Algae attached to the ice bottom or residing within pores in the ice interior are provided with a stable platform for growth, while the size spectrum of the pore space serves to exclude larger grazing organisms (Krembs et al., 2000). Granular ice often contains much larger numbers of microorganisms since frazil-ice formation and aggregation represents a natural concentration mechanism (Thomas and Dieckmann, 2003). Pore microstructure and the extreme brine salinities within individual pores are also of interest as analogs of potential extraterrestrial ice habitats (Thomas and Dieckmann, 2002; *see also* Exobiology).

Hajo Eicken

See also Dissolved oxygen, nutrients and other gases; Exobiology; Ice-core analysis techniques; Isotopes in ice; Pack and fast ice; Polynyas, leads in the Southern Ocean; Precipitation; Sea ice microbial communities and primary production; Sea ice types and formation; Surface energy balance; Thermohaline and wind-driven circulation

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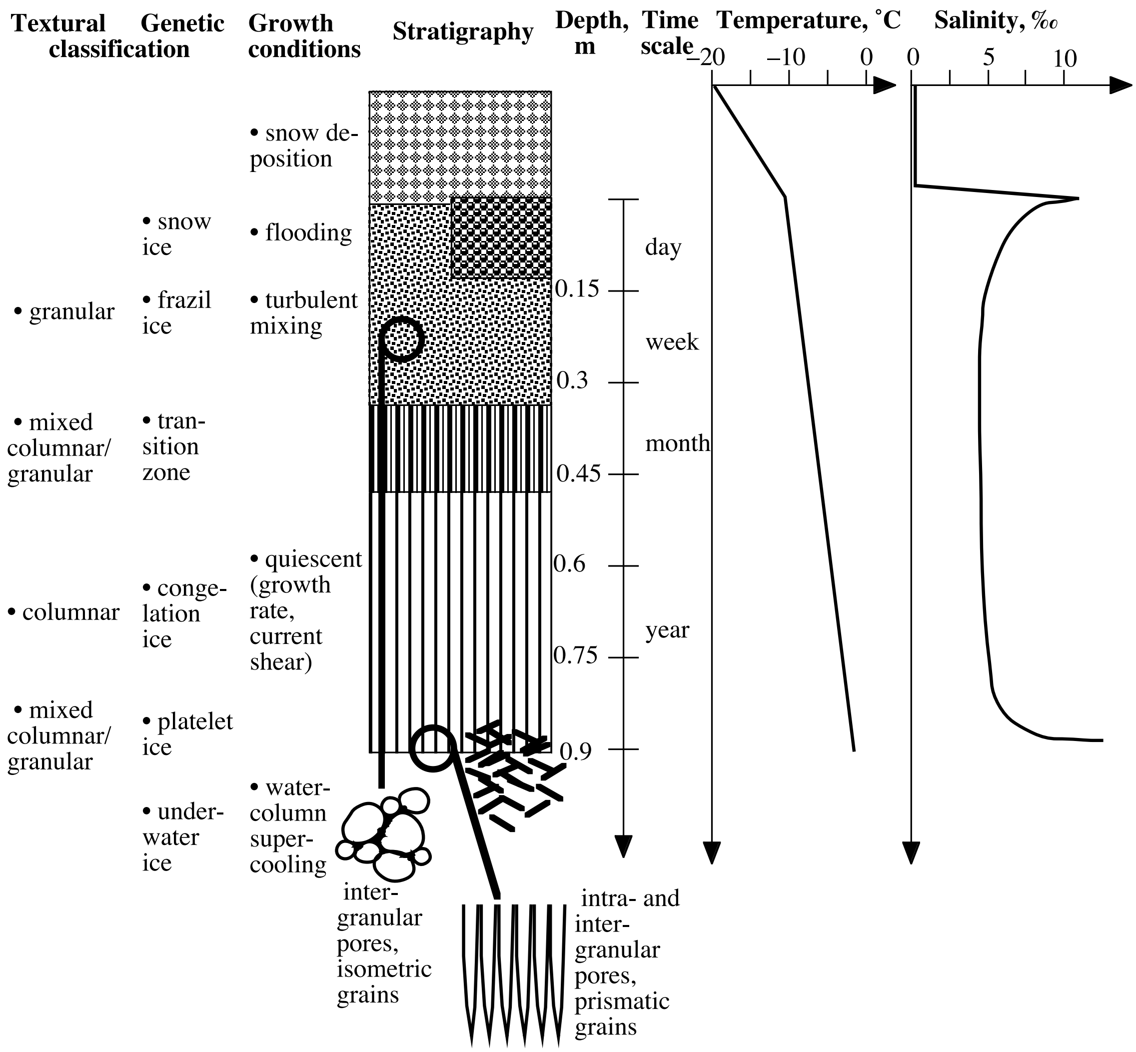
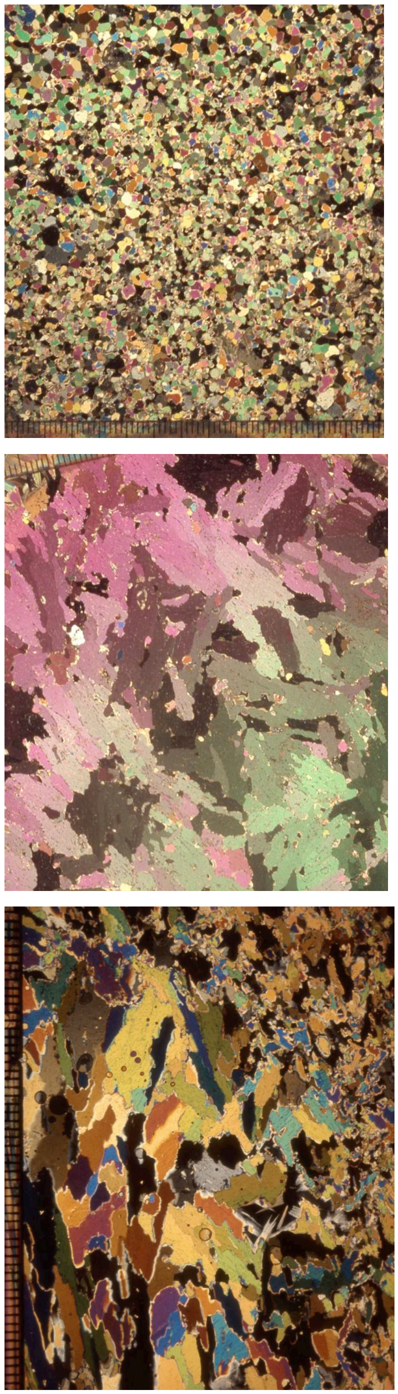


Figure 1: Schematic summarizing the different types of ice texture and microstructure found in Antarctic sea ice, along with a typical vertical profile of temperature and bulk ice salinity in mid-winter.



a

b

c

Figure 2: Thin sections of orbicular granular sea ice formed from frazil ice (a, horizontal section), columnar sea ice grown through congelation of seawater at the base of the ice cover (b, horizontal section) and mixed columnar/granular sea ice formed through consolidation of a mesh of ice platelets accumulating underneath the ice cover (c, vertical section). Samples were obtained in first-year sea ice in the Weddell Sea, Antarctica, and were photographed between crossed polarizers, rendering individual crystals in different colors. Millimeter-scale bar shown at margins of each section.

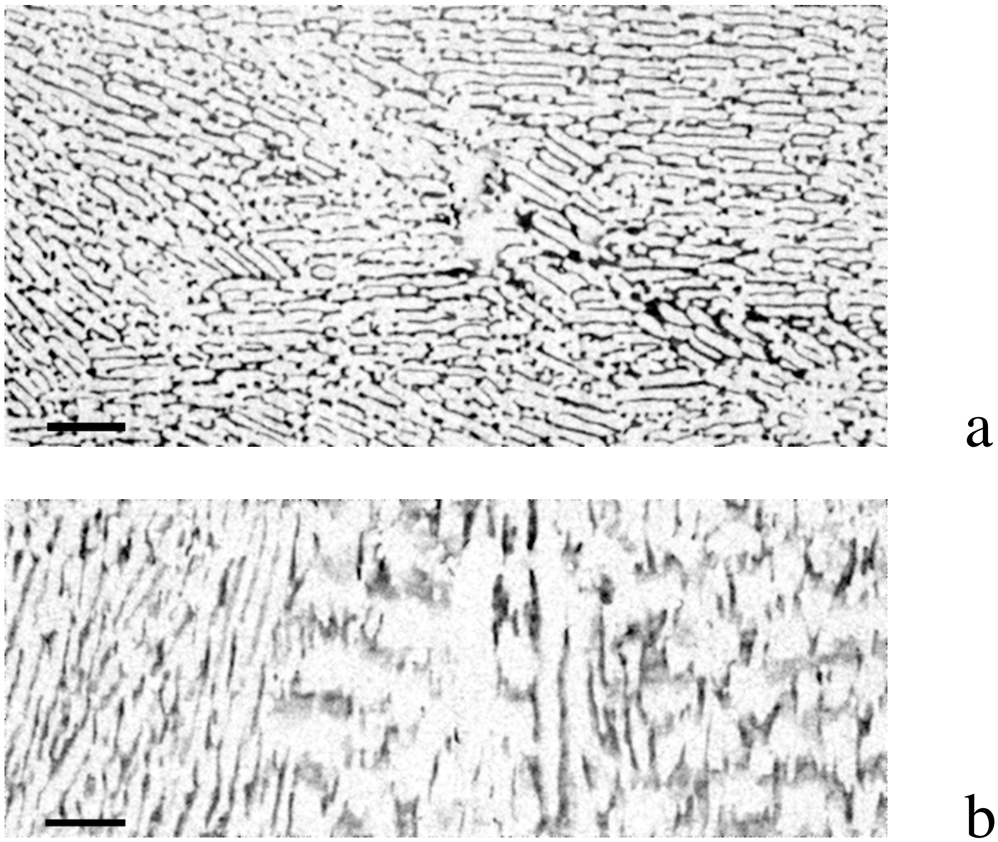


Figure 3: Pore microstructure of artificially grown columnar sea ice obtained through magnetic resonance imaging. Shown are a horizontal (a) and vertical (b) section, with very distinct brine layers (appearing dark) surrounding individual ice lamellae (appearing bright) within each crystal. Cylindrical brine tubes or channels can also be discerned in the central part of both (a) and (b). Note how brine layers mimic grain textures apparent in Figure 2b and c.

a

b

Figure 4: Drilling a sea-ice core with a handheld, combustion-engine powered fiberglass corer in McMurdo Sound, Antarctica (a). Ice core measurements carried out at the drilling site after coring and prior to subsampling (b).