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Geometric properties of platelet ice crystals

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Abstract

Sea ice that forms in McMurdo Sound, Antarctica, which is adjacent to the McMurdo and Ross Ice Shelves, exhibits the uncommon ice fabric, incorporated platelet ice. This ice fabric is the subject of a high resolution thin sectioning study, consisting of ten closely spaced horizontal sections bounded above and below by vertical sections. From these we investigate the crystallographic and geometric properties of the ice grains and find a relationship between c-axis orientation and the minor axis of an ellipse fitted to a crystal's grain boundary. Although accuracy is dependent upon the size and shape of the crystal, the technique provides a means of extracting crystallographic information from historical datasets for which only thin section photographs remain. Identification of common grains in multiple, 2-D sections allows us to reconstruct an approximation of the original 3-D crystal structures. These structures exhibit a variety of growth interactions, including upward directed crystal growth and intertwining crystals. We also construct hypothetical crystal grain boundaries that might be observed for a variety of vertical thin section orientations. These indicate that grain shape can depend on thin section orientation and illustrates some of the limitations of 2-D representations of 3-D crystals. Serrated grain boundaries are identified between neighboring crystals in several vertical sections. Geometric arguments and crystallographic observations lead us to propose a mechanism of layer nucleation within grain boundary grooves that occurs as supercooling exceeds a threshold value.

Keywords: Platelet ice; Sea ice; Thin section; Crystal; Ice shelf; Grain boundary

1. Introduction

Annual sea ice growth in Antarctic waters yields changes in surface cover from a minimum of $3 \times 10^6 \text{ km}^2$ to $20 \times 10^6 \text{ km}^2$ (Gordon, 1981). The variable climatic and oceanographic conditions around the continent combine to produce significant variability in the sea ice properties, both spatially and temporally. The study of sea ice texture and crystallography is used to elucidate aspects of the conditions in which the ice grows.

Previous workers have measured crystallographic properties (e.g., c-axis orientations) to assess prevailing current directions (Gow et al., 1998; Jeffries et al., 1993; Langhorne and Robinson, 1986; Weeks and Gow, 1978); bulk properties (e.g., salinity, stable-isotope) to assess growth rates (Eicken, 1992, 1998; Souchez et al., 1988); and textural classifications to determine growth mechanisms (for example Tison et al. (1998), Weeks and Ackley (1982)).

The existence of platelet ice in the sea ice cover close to an ice shelf is a striking example of the modification to the crystallography by environmental factors. Platelet ice is the name given to an open-textured, random array of dendritic crystals, which may individually have a planar area of tens of centimeters (e.g., Gow et al., 1998; Paige, 1966). Under some conditions these form a loosely-bound, porous layer at the ice–water interface, called the sub-ice platelet layer, which may be meters thick (e.g., Crocker and Wahhams (2004), Dempsey et al. (2010)). The study of the incorporation of these crystals into the sea ice cover, which produces incorporated platelet ice, provides insight into the growth mechanisms and crystal interactions that prevail during sea ice formation.

The aim of this study is to develop and test methods for interrogating sea ice at a macroscopic crystal scale. In particular, we are interested in the grain boundaries between crystals, their 3-D structure and 2-D projections, and the extent to which these are linked to the kinetics of ice growth and environmental conditions present during their formation. Furthermore, by quantifying the contribution of ice growth kinetics to grain geometry, we establish the accuracy of the reverse method, i.e., inferring crystal orientation from the geometric properties of grains. This provides an opportunity to analyze historical datasets for which only a photographic record remains. The

study also allows us to evaluate the ability of 2-D thin sections to represent 3-D crystal structures, thereby identifying potential sources of error and opportunities for textural misclassification.

2. Sea ice growth and texture

The development of incorporated platelet ice is a multi-step process. Ice-ocean interaction at the base of an ice shelf initiates an ice pump (Lewis and Perkin, 1986), which delivers supercooled water, laden with small ice crystals called frazil, to the underside of the adjacent sea ice cover (Foldvik and Kvinge, 1974; Lewis and Perkin, 1986). Buoyancy forces cause thin disks of frazil, or platelets, to rise and settle beneath the underside of the sea ice cover and, provided the flux of loose crystals is large enough (Dempsey et al., 2010), a sub-ice platelet layer develops. The upper portion of this layer is incorporated into the overlying sea ice cover by freezing in the interstices (Jeffries et al., 1993; Smith et al., 2001).

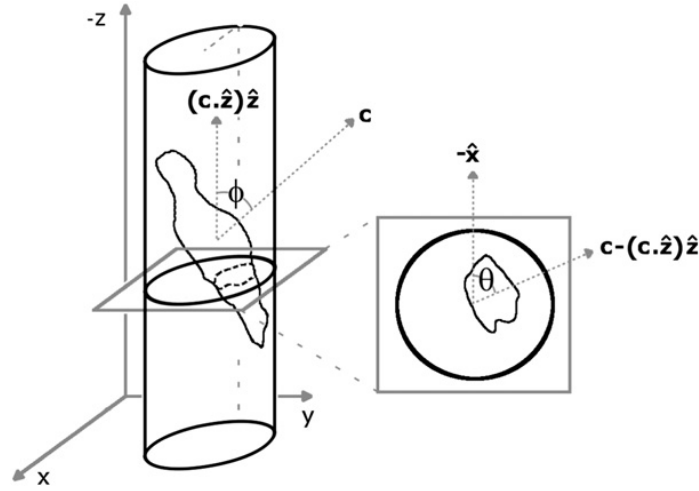


Fig. 1: Conceptual model for a grain produced from 2-dimensional sampling of 3-dimensional ice crystal with c-axis, $\mathbf{c}$, using a horizontal thin section. $\hat{\mathbf{z}}$ is a unit vector in the z direction. $-\hat{\mathbf{x}}$ corresponds to the direction of north. ϕ = c-axis tilt: the angle between the c-axis and vertical. θ = c-axis azimuth: the angle between the horizontal projection of the c-axis and north. In our analysis z is positive downward and $z = 0$ corresponds to the surface.

Incorporated platelet ice presents a variety of crystallographic fabrics when viewed in thin section, and for our purposes it is useful to distinguish three sub-categories; bladed, in which the

68 boundaries between grains are sharp and angular (Fig. 2(a); Eicken and Lange (1989), Gow et al.
 69 (1998), Tison et al. (1998)); draped, in which grain boundaries exhibit millimeter scale serrations
 70 (Fig. 2(b); Tison et al. (1998)); or resumed columnar, where large grains exhibit the lamellar tex-
 71 ture characteristic of columnar ice (Fig. 2(c); Dempsey et al. (2010)). Resumed columnar texture
 72 develops as the supply of platelets from the ocean is reduced and sea ice growth proceeds subject to
 73 geometric selection again. Growth of crystals oriented with c-axes (optic axes) close to the horizon-
 74 tal is favored due to the reduced growth rate parallel to the c-axis (Hillig, 1959). This “resumed”
 75 columnar ice type is distinguished from “traditional” columnar ice, which is produced by geometric
 76 selection amongst granular ice crystals, typically at shallow depths in the sea ice cover.

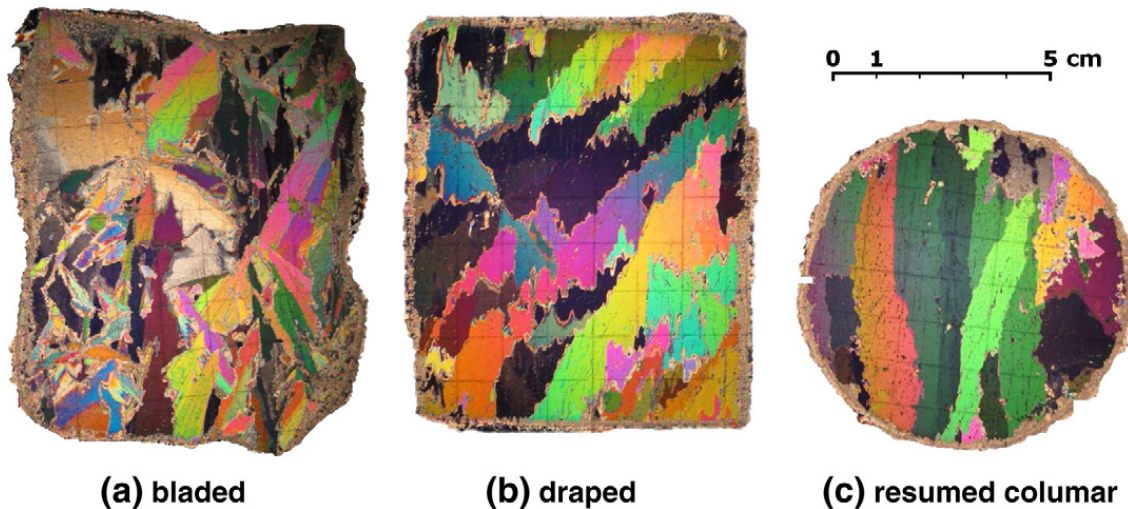


Fig. 2: Comparison of platelet ice fabrics. (a) Bladed and (b) draped platelet ice are shown in
 vertical thin sections. (c) Resumed columnar ice is shown in a horizontal section. All thin sections
 share the same scale.

77 **2.1. Study area**

78 Sea ice samples investigated in this work were collected during a survey of McMurdo Sound, Antarc-
 79 tica conducted during the austral summer of 2007. Ice cores were extracted from six locations along
 80 an east–west transect that traversed the annual sea ice across a distance of 25 km. A detailed
 81 treatment of the textural variability observed in the ice collected by this survey is presented in
 82 Dempsey et al. (2010).

83 Previous surveys of the Sound (Gow et al., 1998; Jeffries et al., 1993; Jones and Hill, 2001;

Leonard et al., 2006; Paige, 1966) have yielded multiple observations of incorporated platelet ice, which comprised up to 50% of the sea ice thickness in some locations. Platelet ice is also a feature of other regions of Antarctica (e.g., the Weddell Sea (Eicken and Lange, 1989), Hells Gate Ice Shelf (Tison et al., 1998)). In this work we examine the growth of incorporated platelet ice by the preparation of a series of horizontal thin sections in close vertical proximity. This is complemented by observations of platelet clusters grown on cables hanging in the water column (see Fig. 3), which illustrate some of the 3-dimensional growth forms observed in the 2007 ice cores. Several features of the growth of platelets attached to cables are similar to ice crystal growth within the sub-ice platelet layer prior to its consolidation by the overlying ice cover. For instance, in both environments a supply of supercooled water acts as a heat sink for further growth of existing crystals (Leonard et al., 2011). Further, while crystal growth attached to the submerged cable are likely to be less constrained by the presence of neighboring platelets, crystal–crystal growth interactions evidently occur (Fig. 3).

3. Method

3.1. Sample preparation

Prior to their extraction, handheld GPS devices were used to mark ice cores with a true north reference direction. Following the removal of a core in several pieces, this reference mark was transferred along the length of the core. At our chosen sample location two cores were extracted in this manner and returned to a cold lab at New Zealand’s Scott Base for further preparation and analysis.

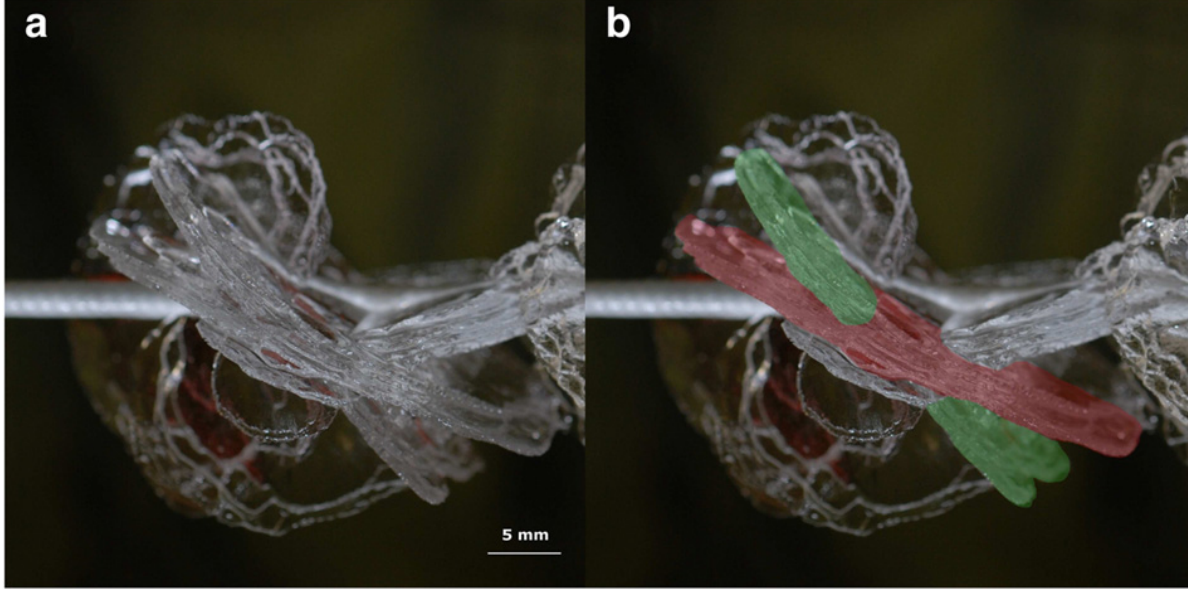


Fig. 3: Intersections of two platelets grown at an angle to one another. (a) Original photo and (b) intersecting platelets highlighted. We propose this as a 3-dimensional representation of the crystals R and G reconstructed in Fig. 9. Photo courtesy of Dr. Craig Stevens, NIWA, New Zealand.

The first core was cut lengthwise to produce a series of vertical sections, approximately 10–20 mm thick. In transmitted light these thick sections provide an indication of the distribution of granular, columnar and incorporated platelet ice, although it is not possible to distinguish between the three platelet sub-categories from these samples. At a selection of depths vertical thin sections were produced by reducing the thickness of the thick sections to less than 1 mm on a microtome. Such thin sections, when viewed between crossed polarizers on a universal stage (Langway, 1958), provide a 2-D projection of individual ice crystals (see Fig. 1). A series of horizontal thin sections, spaced approximately 9 mm vertically, was prepared from the second core. These were photographed between crossed polarizers on a universal stage.

3.2. C-axis measurement

Ice grains in horizontal thin sections are distinguished from their neighbors by the orientation of their c-axes. Following Langway (1958) we measure for each crystal; (i) the c-axis azimuth, θ , defined as the angle of the c-axis projected in the horizontal plane and measured clockwise from the north reference mark; and (ii) tilt, ϕ , defined as the angle between the c-axis and the vertical axis.

118 In this study we have measured c-axis parameters for all grains with an area greater than 20 mm^2
 119 (see Fig. 8(b), section 10 for the smallest grain used in this experiment). While grains below this
 120 threshold are more frequently encountered, they seldom belong to crystals with a vertical extent
 121 greater than 9 mm and therefore do not appear in adjacent sections. Further, these small crystals,
 122 while numerous, comprise only a small proportion of the total sea ice volume.

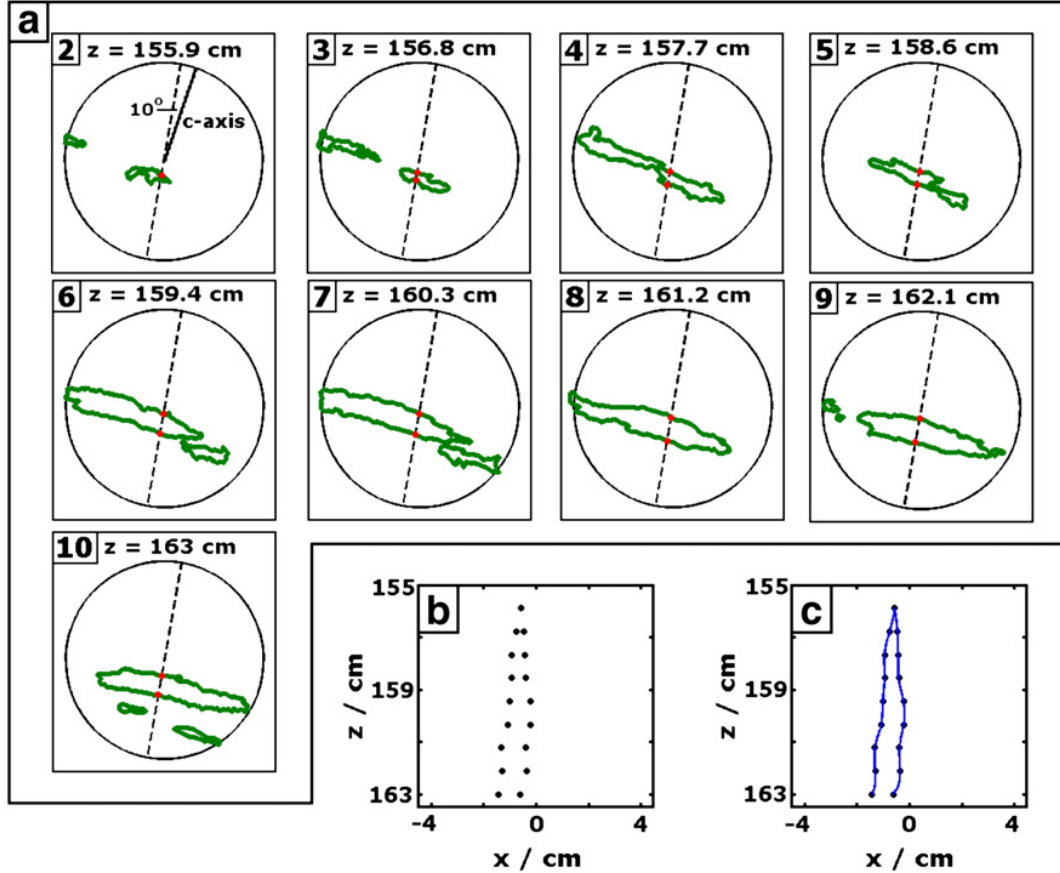


Fig. 4: Construction of vertical thin section. (a) Grain boundaries for crystal G, observed in sections 2–10. Intersections of a vertical plane rotated 10° from crystal c-axis (dashed line) with the grain boundary (solid outline) are marked. The depth of each horizontal thin section is marked. (b) Grain boundary intersections with depth. Note, $x = 0$ corresponds to the core axis. (c) Spline interpolation through grain boundary intersections.

123 A single crystal of ice, providing it is large enough, may end up sampled by two or more horizontal
 124 sections. Grains from adjacent thin sections are judged to have originated from the same ice crystal
 125 based on similarity of c-axis orientation and spatial position. Langway (1958) estimates errors in

measuring θ and ϕ on a universal stage as $\pm 5^\circ$, which provides a useful bound in judging c-axis agreement between vertically adjacent grains.

3.3. Digital analysis

Digitization of thin section images is a necessary step in the reconstruction of a 3-dimensional volume of ice. In previous studies digitized images have been processed to obtain brine feature shape and size (Cole et al., 2004), and automated image analysis of thin sections has been used to provide grain-boundary density and grain cross-sectional area (Durand et al., 2006; Eicken, 1993; Eicken et al., 1994; Gough et al., 2012; Wilen et al., 2003). Digitization also facilitates the calculation of grain parameters and implementation of various least squares fitting methods (Eicken, 1993). Grains are rarely blemish-free and often display brine inclusions, such that care must be taken in designing grain boundary edge detection algorithms. In this study grain boundaries were digitized manually.

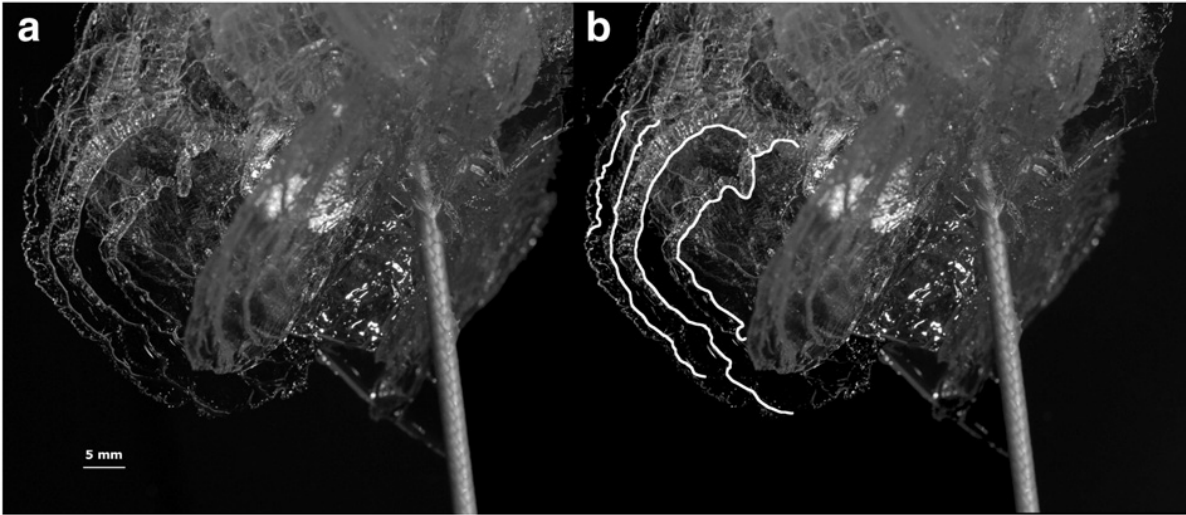


Fig. 5: Evidence for nucleation of discrete layers on the basal plane of platelet crystals grown attached to submerged cables. (a) Original image is presented along with (b) highlighted layer boundaries. The crystal of interest is a multi-layered disk roughly in the plane of the picture. Photo courtesy of Dr. Craig Stevens, NIWA, New Zealand.

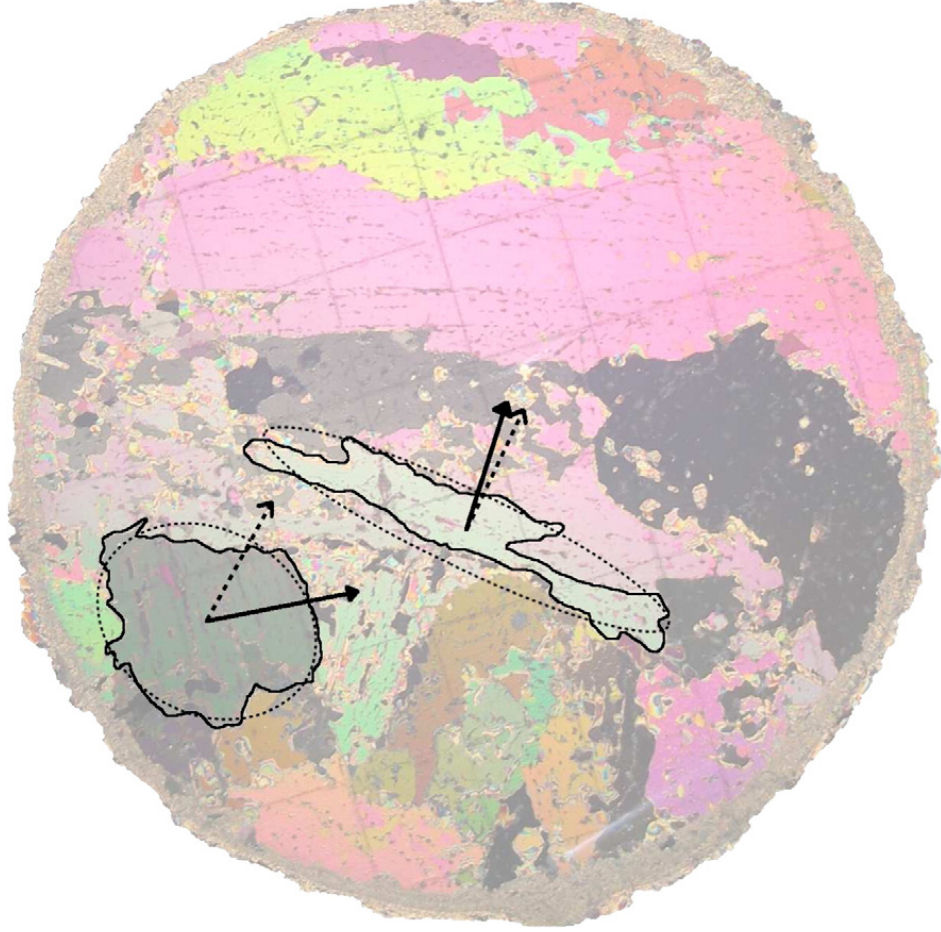


Fig. 6: Demonstration of ellipse fitting to two sample grains. Solid contours mark outline of grain boundaries. Dashed outline shows the ellipse fitted through the grain boundary that minimizes the least squares error between the digitized boundary and approximated shape. Solid and dashed arrows are respectively measured and fitted projections of c-axis directions onto the horizontal plane.

We build a partial reconstruction of a 3-dimensional ice crystal by tracking its presence in a series of adjacent horizontal thin sections. From this reconstruction we derive particular aspects of its growth and interaction with neighboring crystals.

In Fig. 4 we consider the intersection of a reconstructed crystal with a hypothetical vertical observation plane, oriented at some angle from the crystal's c-axis. This process is analogous to the extraction of a vertical thin section of ice along the same orientation. Due to the coarse nature of this thin section study, grain boundaries cannot be resolved vertically to an accuracy better than 9 mm. Spline interpolation between the available points produces a first order approximation to

the vertical grain boundary.

If ice growth was unconstrained, discoid crystals would result because growth in the basal plane is kinetically favored relative to growth parallel to the c-axis (for example see Fig. 5). These crystals are approximated as ellipsoids in numerical modeling studies of platelet ice fabrics (Dempsey, 2008). The intersection of a discoid crystal with a horizontal plane, for instance during thin section sampling, yields grains that are approximately elliptical in shape. This simplified crystal shape does not account for dendritic growth perturbations (such as shown in Fig. 5) or interactions with adjacent crystals, however we expect an ellipse to provide a useful, first-order fit to a grain outline. In Fig. 6 we show the process by which an ellipse is fitted to the outlines of two grains in a digitized thin section image. This process uses an algorithm that minimizes the least squares error between pixels comprising the grain boundary and the equation of the fitted ellipse. The minor axis of the ellipse approximates the horizontal projection of the c-axis, and is thus a measure of θ . The major axis of the ellipse lies approximately within the basal plane, along which ice growth is kinetically favored.

The concept of a grain's minor axis closely corresponding to the horizontal projection of its c-axis is not novel. In fact, a common approach when making c-axis measurements on a universal stage is to initially align a grain as if its c-axis was perpendicular to its long dimension, i.e., its major axis. Our method attempts to formalize this process to estimate c-axis orientations directly from a thin section photograph. We also investigate the error associated with ellipse fitting, as a function of grain size and shape, to establish the utility of this technique.

4. Results and discussion

4.1. Overview and selection of core for high resolution study

In this work we study platelet fabrics that are typical of the sea ice on the eastern side of McMurdo Sound (Dempsey et al., 2010; Gough et al., 2012; Leonard et al., 2006). Samples were extracted from a site (coordinates: [165° 06.678 E, 77° 40.070 S]) in November and December of 2007 (Dempsey et al., 2010). An initial inspection of the first core from the site indicated that the ice fabric was primarily columnar for the top meter, punctuated at 0.5 m by a small length of incorporated platelet ice (see Fig. 7). From 1 m depth draped platelet fabric is observed and continues to a depth of 1.6 m. Bladed platelet fabric is observed at the base of the 2.1 m core and no sub-ice platelet layer

173 was encountered at the time of sampling (1 December 2007). However, the absence of a sub-ice
 174 platelet layer at the time of sampling does not preclude its presence at previous times during the
 175 winter. The appearance of large platelet crystals incorporated into the ice cover indicates in situ
 176 growth of these crystals. Gough et al. (2012) have demonstrated that when there is no sub-ice
 177 platelet layer smaller crystals disrupt geometric selection, while the presence of this layer results in
 178 larger platelet ice crystals in the sea ice fabric.

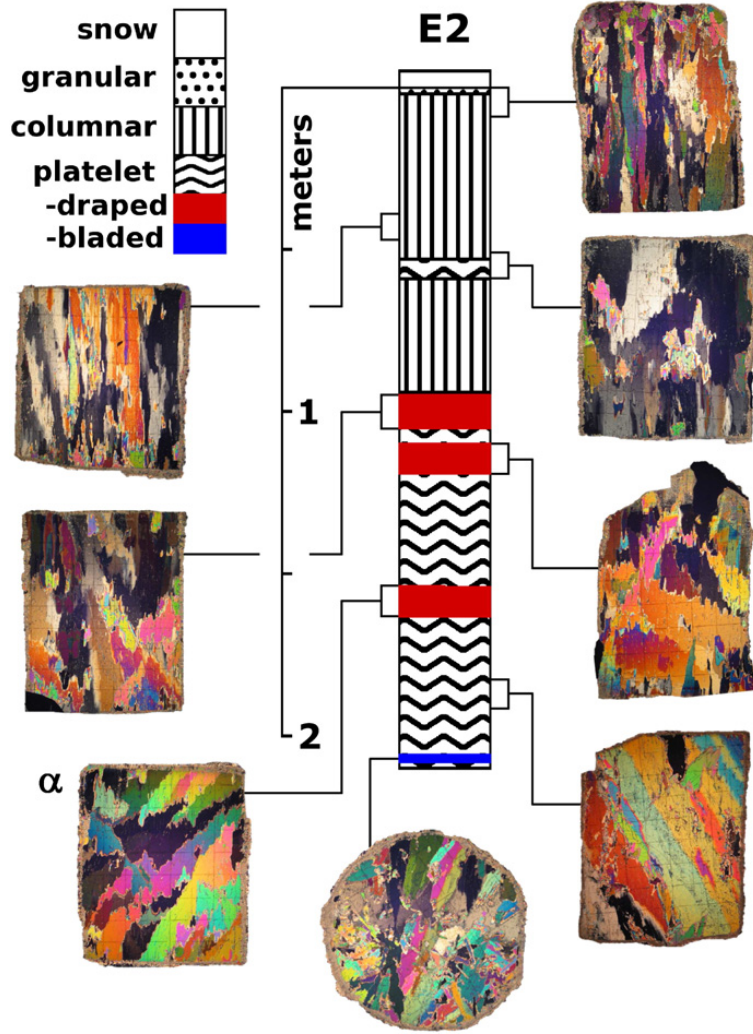


Fig. 7: Sea ice composition at 165° 56.784 E, 77° 39.500 S, adapted from Dempsey et al. (2010).
 The lower left vertical section, marked α , was chosen for further study by high resolution thin
 sectioning.

179 Serrated grain boundaries, a term we use here to describe millimeter scale perturbations along

a grain boundary, is observed in a vertical section of draped platelet ice at a depth of 1.6 m. As a partial 3-dimensional crystal structure might illuminate the growth of draped platelet fabric and serration along the grain boundaries, this depth interval was chosen for detailed study. We note that a high resolution thin section study might also be applied at a depth of ~ 1.2 m, as the vertical section at this depth (Fig. 7) indicates serrated grain boundaries at least as pronounced as those at 1.6 m. However, grains at 1.6 m show greater vertical extent, and thus horizontal sectioning at this depth is likely to image the 3-D crystal forms in greater detail.

4.2. Reconstructions and insights

Ten horizontal thin sections, numbered 1 to 10 with increasing depth, were prepared from the second core at a depth of 1.55 to 1.63 m. Vertical thin sections were prepared immediately above and below the horizontal sections and were cut along a plane that includes the north–south axis. These sections were imaged between crossed polarizers and are presented in Fig. 8(a–b).

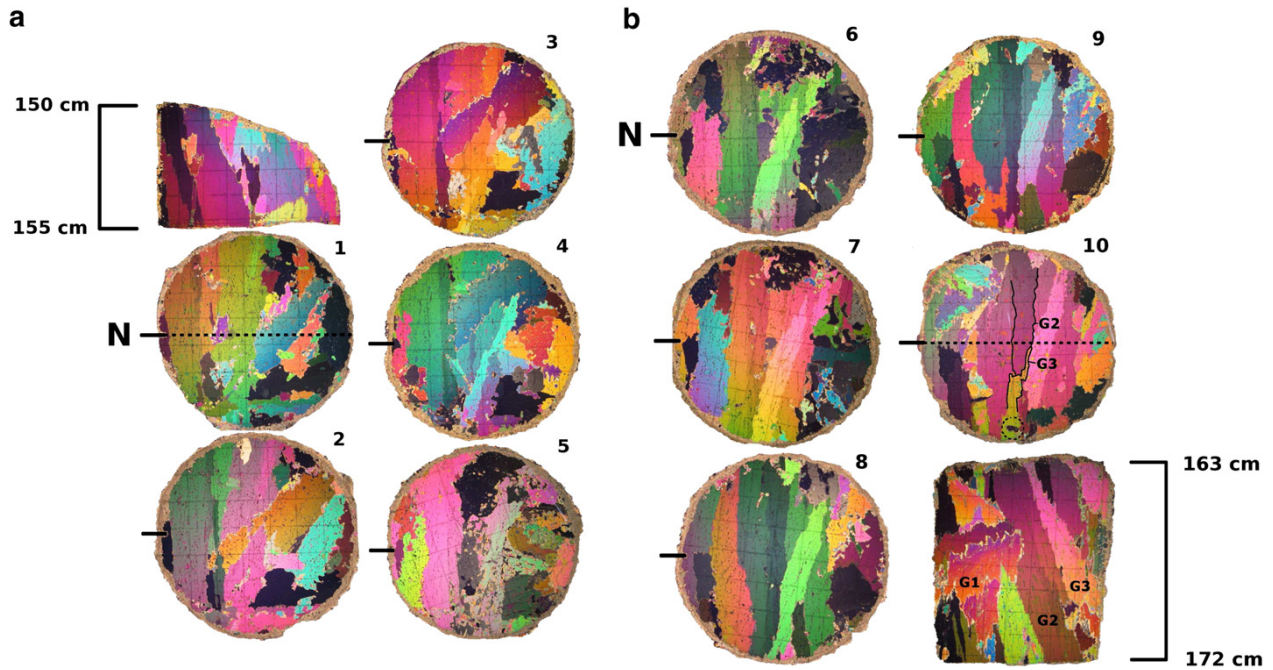


Fig. 8: (a) Upper bounding vertical section and upper five horizontal sections of the high resolution thin sectioning study. Note grains in adjacent thin sections belonging to the same 3-dimensional crystals are not required to be in the same color. Dashed line in horizontal section 1 marks the axis of the upper bounding vertical section. North is marked on each horizontal section by a solid dash. Grid is 1 cm×1 cm and has not been aligned along the North azimuth. (b) Lower five horizontal sections and lower bounding vertical section of the high resolution thin sectioning study. Dashed line in horizontal section 10 marks the axis of the lower bounding vertical section. Dashed circle in horizontal section 10 indicates the smallest crystal digitized in this study. Several grains have been marked in the lower horizontal and vertical section and are referred to in the text.

From the horizontal sections we observe that the ice structure is dominated by several large crystals containing evenly spaced rows of brine pockets. Many of these crystals have planar areas greater than 10 cm², and present in all ten horizontal sections and have been identified in the upper and lower vertical sections on the basis of relative position. These crystals, which occur below the onset of incorporated platelet ice, have c-axes that lie close to the horizontal plane and, along with observations of their lamellar texture, we classify them as resumed columnar (Dempsey et al., 2010). In addition, a number of isolated crystals are observed, with a variety of c-axis tilts, which suggests that crystals originating in the water column are attaching themselves at random orientations to

the base of the sea ice.

C-axis measurements made on grains from the thin sections identify 108 separate crystals in the 400 cm³ volume of core. These were sampled 249 times by the ten thin sections (which includes only those grains with area larger than 20 mm²). Thin sections were photographed and grain boundaries digitized as outlined in Section 3.3.

Reconstructions of several extensive crystals raise interesting questions regarding the nature of growth in the sub-ice platelet layer. Three reconstructed crystals are presented in Fig. 9, referred to here by their shading red (xtitR), green (*G*) and blue (*B*). *G* is laterally extensive, well established in section 1, and is a dominant feature through to section 10. *B* is extensive in section 1 and trends eastward with depth such that it is nearly absent from section 6. *R* first appears in section 2 and persists to section 10, at which depth it is a prominent feature of the ice.

Of particular interest in this reconstruction is the initial appearance of crystals *B* and *R*. Rather than appearing as a single grain, which is typical of the majority of crystals in this study, each crystal initially appears in two disconnected locations, i.e., the grain is not continuous. In the sections below these initial appearances (one below for *B* and two for *R*) the disconnected grains merge, suggesting that the upper surface of the crystal is characterized by two ‘prongs’. Furthermore, having become continuous in section 4, *R* becomes disconnected once more in section 6 and again in sections 9 and 10.

We identify three possible scenarios for the appearance of such a pronged crystal structure (see Fig. 10(a)–(c)). First (Fig. 10(a)), two platelet crystals are independently advected to the underside of the sea ice where they settle with identical c-axis orientations. Growth of these two crystals downward and laterally causes their surfaces to meet and fuse into a single larger crystal. However, the likelihood of two platelets settling with imperceptibly different c-axis orientations is considered negligible and this scenario is rejected.

Alternatively, the crystal may have originated within the water column with the pronged structure already grown. Advection to the sub-ice platelet layer and subsequent consolidation of ice around the crystal would produce the observed structure. However, observations of platelets in the water column do not indicate the presence of such structures at the required magnitude, i.e., prongs that extend 10–20 mm from the body of the crystal.

Instead, we favor a third scenario involving advection of a crystal into the sub-ice platelet layer

230 and subsequent in situ growth. Once the crystal is settled, in addition to ice growth directed
231 downward, we postulate growth upward into two pre-existing voids produced naturally by the
232 porous ice matrix (see Fig. 10(g)–(i)). Such voids might originate as grain boundary grooves, in
233 which the basal planes of two ice crystals diverge downward and a gap is created between them.
234 The exposed surfaces within the groove are crystallographically flat and the void is thus stable until
235 a supercooling of ≈ 0.03 K is achieved (Hillig, 1959). The advected crystal then acquires a pronged
236 shape through upward directed growth along its basal plane, for which the required supercooling is
237 less than that for growth on the groove walls. While we have not extracted sufficient information
238 from the ice to establish the validity of such a scenario, the case for upward directed growth is
239 compelling. Video images of the sub-ice platelet layer (Smith et al., 2001) suggest a sufficient
240 proportion of void space and platelet complexity to accommodate such growth.

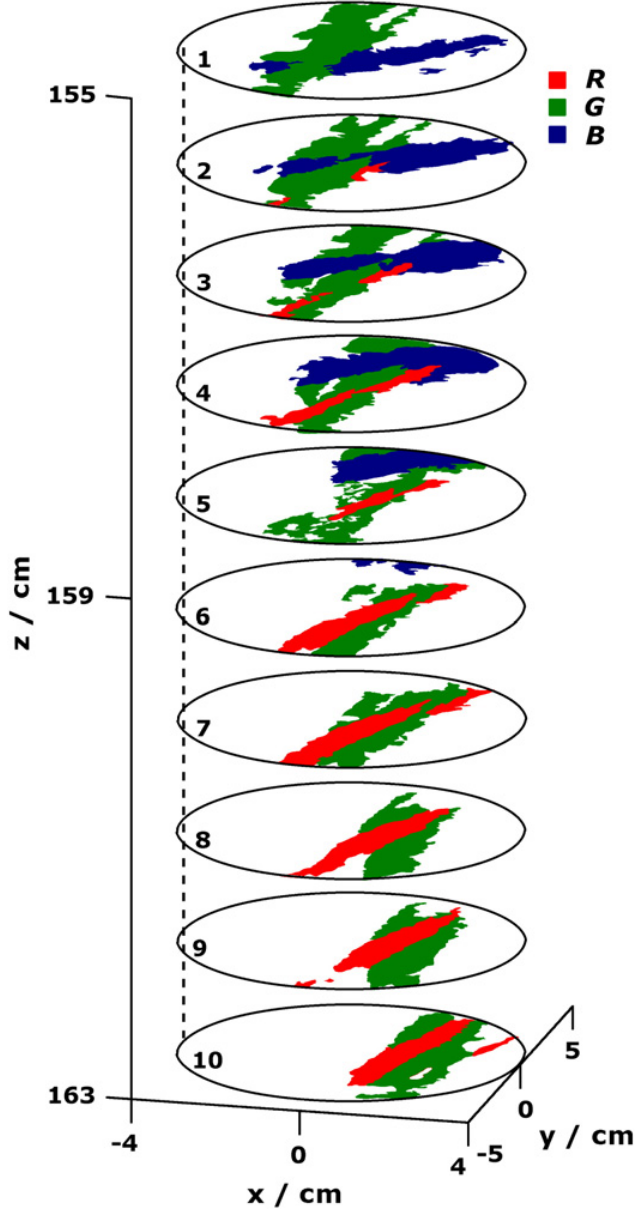


Fig. 9: Three-dimensional reconstructions. Three extensive resumed columnar crystals are labeled (R), (G) and (B). The core boundary is marked by solid circles and has been oriented with north along the dashed line. The vertical axis has been scaled by a factor of three for clarity. C-axis azimuths measured on the universal stage — $G=353^\circ$, $B=122^\circ$, $R=342^\circ$.

241 The reconstruction presented in Fig. 9 also shows an unusual interaction between crystals G
 242 and R , which appear to have grown competitively, the growth of one impinging on and intersecting
 243 the other. However, rather than consistent dominance of one crystal over the other, roles are

interchanged at different depths, i.e. G intersects R in sections 2, 3 and 4, then R briefly intersects G in section 5, before G once more regains dominance in sections 6 and 7. Finally, for the remaining sections 8, 9 and 10 R is once more dominant and intersects G . Complementing this observation, we present photographic evidence from platelet clusters grown on submerged cables. Fig. 3 shows two platelets intersecting at $\approx 30^\circ$ to each other. Thin sections prepared in the plane of this photograph would sample this intersecting behavior and yield grain structures similar to those observed for G and R , although there is no suggestion of interchanging dominance here. These observations provide further testimony of platelet growth within an environment constrained by adjacent crystals.

4.3. Dependence of grain shape on sample plane

Following Section 3.3, reconstructions of vertical thin sections were prepared for three prominent crystals, R , G and B , for sample planes oriented at 0, 45 and 90° from the crystal's c-axis (Fig. 11). For crystal R sampling at orientations between 0 and 70° yields a narrow outline that is stretched in the vertical dimension. This form is qualitatively similar to several grains ($G2$ and $G3$) in the lower vertical section of Fig. 8(b), identified as resumed columnar. At higher angles of sampling the outline thickens laterally as the intersecting plane cuts the crystal sub-parallel to the basal plane. The resulting form is now more similar in shape to grain $G1$ in the lower vertical section of Fig. 8(b) and the grains in section α in Fig. 7, identified as a draped platelet fabric.

Crystal G shows similar behavior to R such that for a thin section oriented perpendicular to the c-axis, the grain occupies the width of the section. However, there are several grain boundaries within the larger outline (data points within the interpolated grain boundary), which suggests the grain is not continuous throughout. These results suggest that grain shape and boundary features may be related to the plane of observation, particularly when it is oriented close to the basal plane. Consequently, care must be exercised in textural analysis of grain forms in vertical sections as a wide variety of 2-D fabrics may be derived from a set of similar 3-D crystal structures. For instance, in this work we have distinguished between grains of draped platelet and resumed columnar ice. However Fig. 4.3 indicates that these differences may be superficial and largely a product of the particular plane of observation.

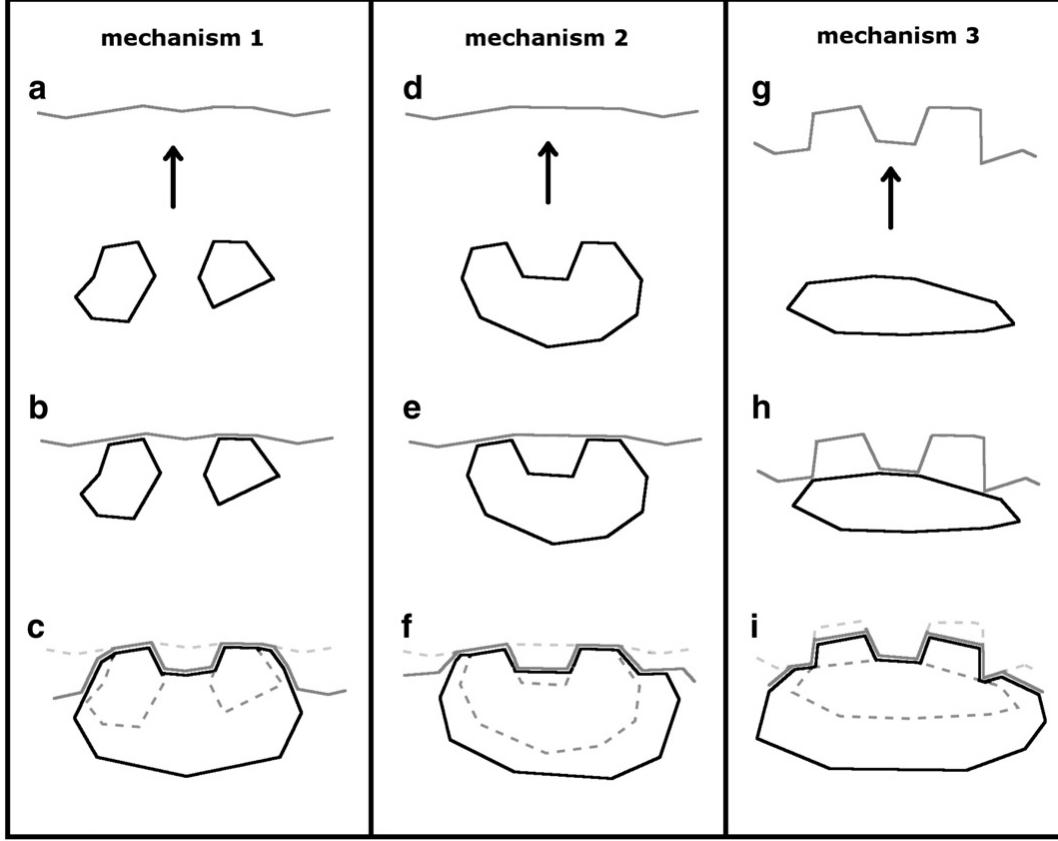


Fig. 10: Three proposed mechanisms for development of a pronged crystal structure. All three involve an initial advection step followed by growth of the interface, marked by a gray solid line, and growth of the crystal, marked by a black solid line. In the final step of each mechanism the outline of the interface and crystal prior to growth is marked by a dashed outline.

4.4. Fit of ellipses

In Section 3.3 we proposed that a discoid ice crystal sampled by a horizontal thin section would yield a grain whose boundary, to a first approximation, could be described by an ellipse (see Fig. 6). For each of the 249 grains in this study, an ellipse of eccentricity, e , was fitted to its boundary, and the angle between the minor axis and north, θ' , obtained. Our conceptual model for discoid ice crystals predicts the minor axis to be oriented along the c-axis azimuth, θ , and consequently we define the deviation between the fitted and observed azimuth, $\Delta\theta = \theta - \theta'$. Using bootstrap sampling methods (Efron and Tibshirani, 1986) the mean and standard deviation of this distribution of θ were calculated and bounded by 95% confidence intervals. These are, respectively, -2.0° within

an interval of $[-4.6 \text{ } 2.6]$ and 28.9° within an interval of $[24.9^\circ \text{ } 34.1^\circ]$. As ellipse fitting does not provide a measure of c-axis tilt, ϕ , no distinction can be made between a grain of θ or $\theta + 180^\circ$. Consequently, θ lies in the range -90 to 90° .

The accuracy of this method depends on the extent to which a given grain expresses its crystallographic properties in its geometric features. For instance, greater confidence would be expected for an ellipse fitted to a grain of particularly pronounced elongation (parameterized by the eccentricity, e). Similarly, for larger grains an ellipse fit will be less influenced by small deviations to the boundary, e.g., random growth perturbations or crystal impingements. These ideas are quantified in Fig. 12(a–b), which shows the error of the ellipse fitting method as thresholds based on grain area (Fig. 12(a)) and eccentricity (Fig. 12(b)) are applied to the sample. Discarding smaller grains results in a reduction in error (see Fig. 12(a)), although a sample size anomaly causes an increase for a threshold between 120 and 280 mm^2 . Imposing a threshold on grain elongation also improves the accuracy of the method.

Fig. 12(c–d) demonstrates reduction in error that can be achieved by applying arbitrary thresholds of area greater than 300 mm^2 and eccentricity greater than 0.87. From the original sample of 249 grains, 47 exceed the chosen thresholds, and the error of the ellipse fitting method is now 6.0° , within 95% confidence bounds of $[4.7^\circ \text{ } 8.6^\circ]$.

Fig. 12(c) plots the unfiltered sample of observed c-axis azimuths, θ , versus the values predicted by the ellipse fitting method, θ' . The raw data exhibits considerable scatter about the 45° line, which represents a perfect match between θ and θ' . However, in applying thresholds we observe that the less accurate data points are removed and the prediction improved for the remaining grains (Fig. 12(d)). These two datasets, unfiltered versus strongly filtered, demonstrate the implicit trade-off associated with this method; error reduction is achieved at the expense of data exclusion.

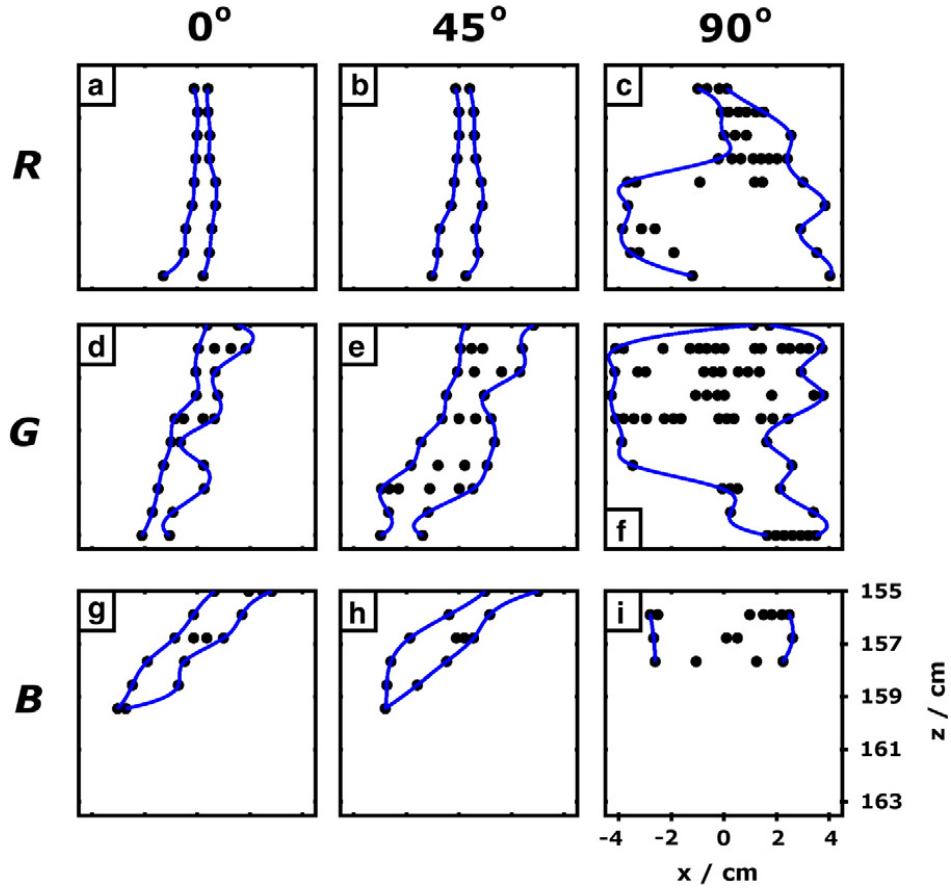


Fig. 11: Vertical single crystal reconstructions from horizontal thin sections. Crystals R , G , and B are reconstructed for vertical planes oriented 0° , 45° and 90° from crystal's c -axis. Black dots indicate grain boundary intersections, which are interpolated using splines to produce a grain boundary for the vertical section. In some instances there are more than two grain boundary crossings for a plane through a single section and these are represented as black dots internal to the grain boundary interpolation.

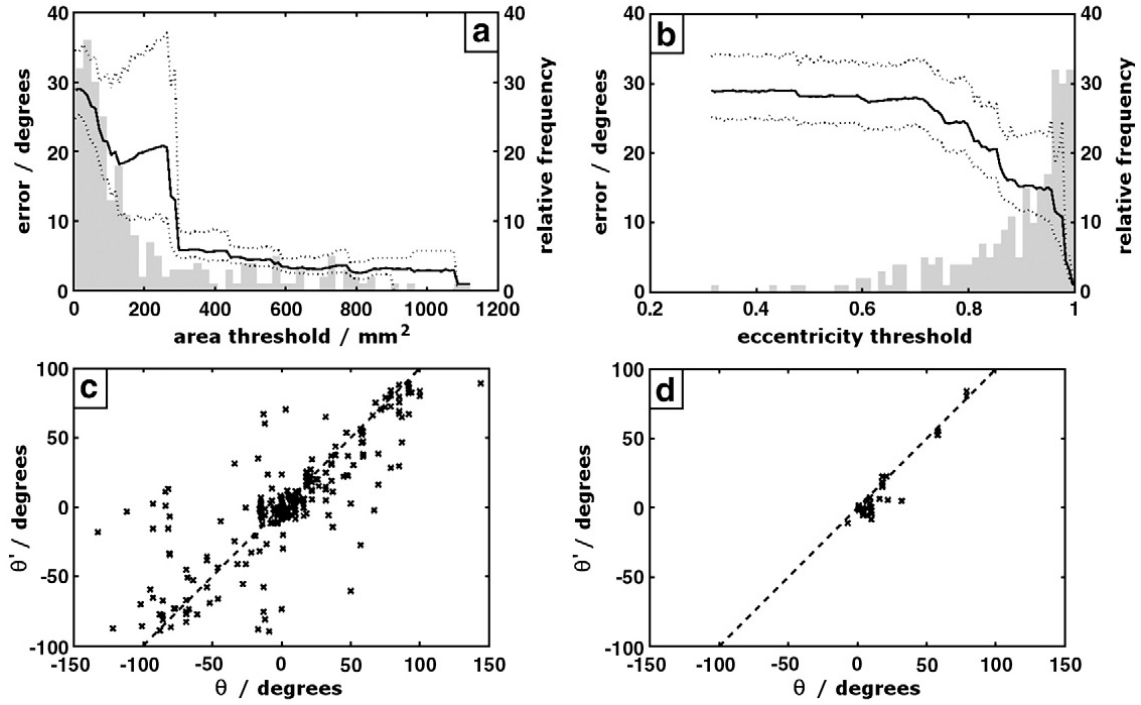


Fig. 12: Accuracy of the ellipse fitting method as threshold values are imposed to (a) area and (b) eccentricity. The error (solid line) and a 95% confidence bounds (dotted line) are superimposed on histograms of relative frequency distributions to provide an indication of the sample proportion above and below a chosen threshold. (c) Observed c-axis azimuth plotted against the value yielded by the ellipse fitting method. The distance of each point from the 45° line (dashed) indicates the error of the fit. The full sample of 249 crystals is presented in (c) and the reduced sample of 91 grains with thresholds of $A \geq 300 \text{ mm}^2$ and $e \geq 0.87$ is presented in (d).

Although this method does not match the accuracy of direct measures of the c-axis azimuth performed on a universal stage ($\pm 5^\circ$ in Langway (1958)), its principle advantage is its low cost and hands off qualities. The method requires only a digital photograph of the thin section and a means of identifying grain boundaries. Machines that measure c-axis orientations automatically, while available (Eicken, 1993; Yun and Azuma, 1999), are expensive, while the method presented offers a first order measure of c-axis azimuth with increased confidence in accuracy for large, elongated grains. The technique is also useful in circumstances where original ice cores are unavailable, but sufficient documentation of the ice remains. For example, it would be possible to undertake a retrospective analysis of historical datasets providing that photographic images of core thin sections

can be obtained.

4.5. Grain boundary serration

Serrated grain boundaries are a common feature of incorporated platelet ice (Dempsey et al., 2010; Gow et al., 1998; Jeffries et al., 1993) and are defined here as millimeter scale perturbations along the grain boundary. Serration is observed on grains of draped platelet fabric in vertical sections in Fig. 8(a–b). One grain boundary in particular is identified from the lower vertical section of Fig. 8(b), exhibiting seven such perturbations (see Fig. 13). Crystals $G2$ and $G3$ are co-identified in horizontal section 10 and the lower vertical section (Fig. 8(b)), due to the near proximity of these sections. The lower vertical thin section was cut along the north–south axis, while the c-axes of $G2$ and $G3$ lie close to the north–south plane. Consequently, interpretation of the grain boundary is likely to be simplified because the c-axes of $G2$ and $G3$ lie approximately in the plane of Fig. 13. The distortion of grain shape caused by sampling along a plane close to the basal plane, as described in Section 4.3, is therefore minimized.

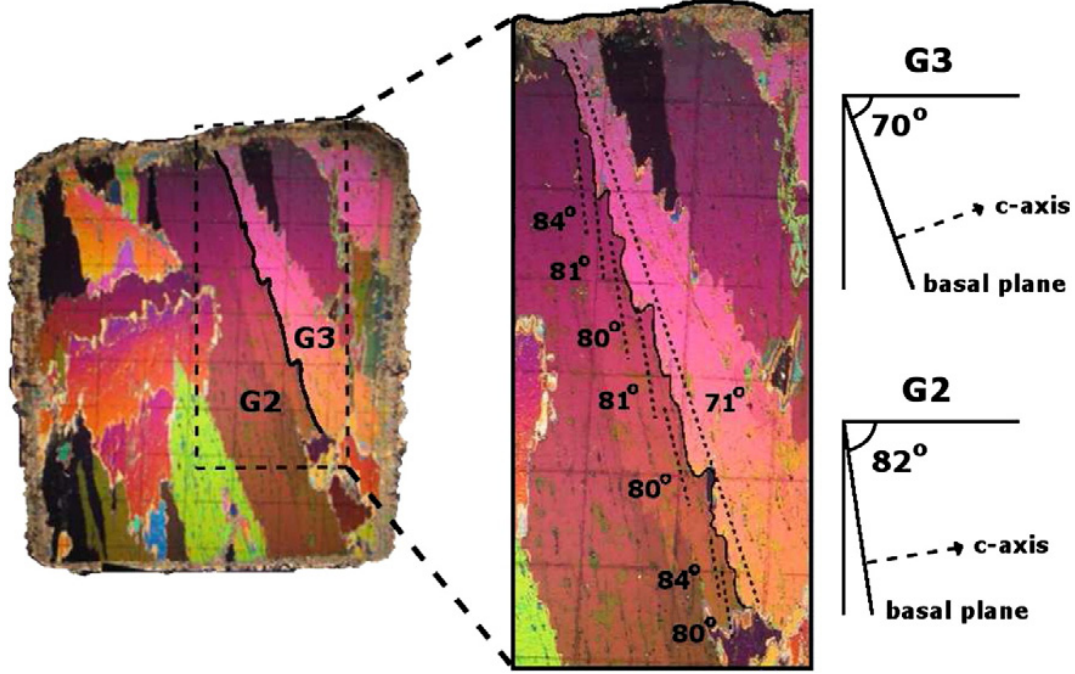


Fig. 13: Serrated grain boundary observed between crystals $G2$ ($\theta = 359^\circ$, $\phi = 82^\circ$) and $G3$ ($\theta = 350^\circ$, $\phi = 70^\circ$). Dashed lines indicate the average trend of seven serrated segments and the overall trend of the grain boundary and angles are measured clockwise from the horizontal. Grid is 1 cm $\times$ 1 cm. Orientations of the basal planes and c-axes for $G2$ and $G3$ are also shown.

The c-axis tilts of grains $G2$ and $G3$ were measured using the universal stage and are $\phi = 82^\circ$ and $\phi = 70^\circ$, respectively. The mean angle of the grain boundary, measured clockwise from the horizontal, is 71° (see Fig. 13), while the steeper segments between the serrations have an average angle of 81° to the horizontal. We note a close correspondence between these observed angles and the c-axis tilts, ϕ , in other words, serrations develop their long axes along the direction of the basal plane. Based on this observation we propose a mechanism of growth by layer nucleation within grain boundary grooves (see Fig. 14).

Where two crystals grow adjacent to one another such that their basal planes diverge downwards, a grain boundary groove forms comprising a steeply dipping surface (grain $G2$) and an opposing overhanging surface (grain $G3$). The exposed surfaces are crystallographically flat and no growth can occur on them until a supercooling of ≈ 0.03 K is achieved (Hillig, 1959). As the ice-water interface advances and the groove deepens, the temperature at the root of the groove lowers in thermodynamic equilibrium with the sea ice temperature gradient (Wilén and Dash, 1995). When

the root is supercooled to ≈ 0.03 K, a growth perturbation develops on the basal plane of the steeper crystal. The data here are not sufficient to establish cause for the perturbation to form on this crystal, as opposed to the overhanging one; however, the steeper temperature gradient in $G2$, compared with $G3$, might favor basal growth on the steeper crystal. Alternatively, the non-symmetric geometry of the groove might favor more efficient convective removal of salt from the basal surface of the steeper crystal. Regardless, the growth perturbation seeds a new layer that grows rapidly toward the ice–water interface. At the root of the groove some growth occurs on the overhanging crystal and a serration is formed. Thus, the grain boundary groove is filled by a series of stacked layers, each tilted at the angle of the steep face, but stacked such that the crystal they comprise trends at the angle of the overhanging face. The method described has features in common with dendritic growth in metallic alloys discussed by Rappaz and Gandin (1993), although we emphasize that the mechanism, as presented here, is specific to serration on boundaries between crystals that are crosscut approximately perpendicular to the basal plane. Where crystals are crosscut much closer to the basal plane, a 3-D extension of the mechanism in Fig. 14 would be required to account for grain boundary serration.

Evidence for layer nucleation is observed in photographs of platelets grown attached to submerged cables in supercooled water (see Fig. 5). The broad platelet occupying the bottom left of the photograph shows several concentric boundaries on the basal plane that follow the approximate contour of the platelet edge. We suggest that these are layers of discrete thickness growing on the smooth basal surface, and that a new layer seeds each time the required supercooling is achieved on the basal plane. In McMurdo Sound, such supercooling persists in the upper meters of the water column through much of the year (Leonard et al., 2011; Mahoney et al., 2011). Cable-grown platelets are shown in an observation plane approximately perpendicular to the basal plane in Fig. 3; stacks of several discrete platelets are evident in this image.

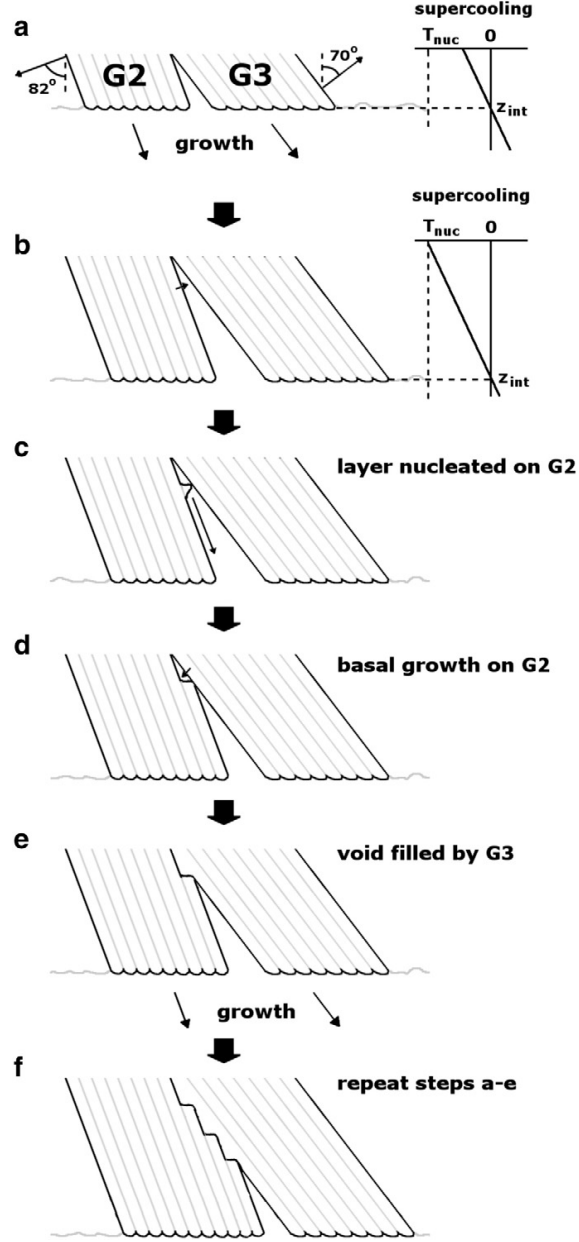


Fig. 14: Proposed mechanism for growth of serrated grain boundaries. (a) A groove develops through divergent growth of crystals $G2$ and $G3$ with c-axes and tilt angles shown. Supercooling within the groove is below the threshold, T_{nuc} , required for nucleation of a new layer on $G2$. (b) Supercooling within the groove increases with further growth until a new layer is nucleated. (c) The new layer grows rapidly along its basal plane. (d) Growth on $G3$ fills the void created between the new layer and the root of the groove. (e) Growth of $G2$ and $G3$ continue until supercooling once more reaches the threshold for nucleation of a new layer. (f) A serrated grain boundary develops through repeated cycles of steps (a)–(e).

Grain boundary serration is directly observed in vertical thin sections but its presence can also be inferred in horizontal sections. In Fig. 15 we show that a serration is characterized by three grain boundary intersections when considering a horizontal transect through the perturbation. A single intersection is observed for transects elsewhere along the grain boundary. The presence of grain boundary serration is thus inferred in horizontal sections by identifying similar sets of three adjacent boundary intersections. Several such instances have been identified in the ten horizontal sections in Fig. 8(a–b), of which two are presented in Fig. 15. These take the form of small, isolated satellite grains embedded in a neighboring crystal. These inclusions are typically elongated with a long axis parallel to the main grain boundary and their limited lateral extent provides some insight into the 3-dimensional character of grain boundary serration.

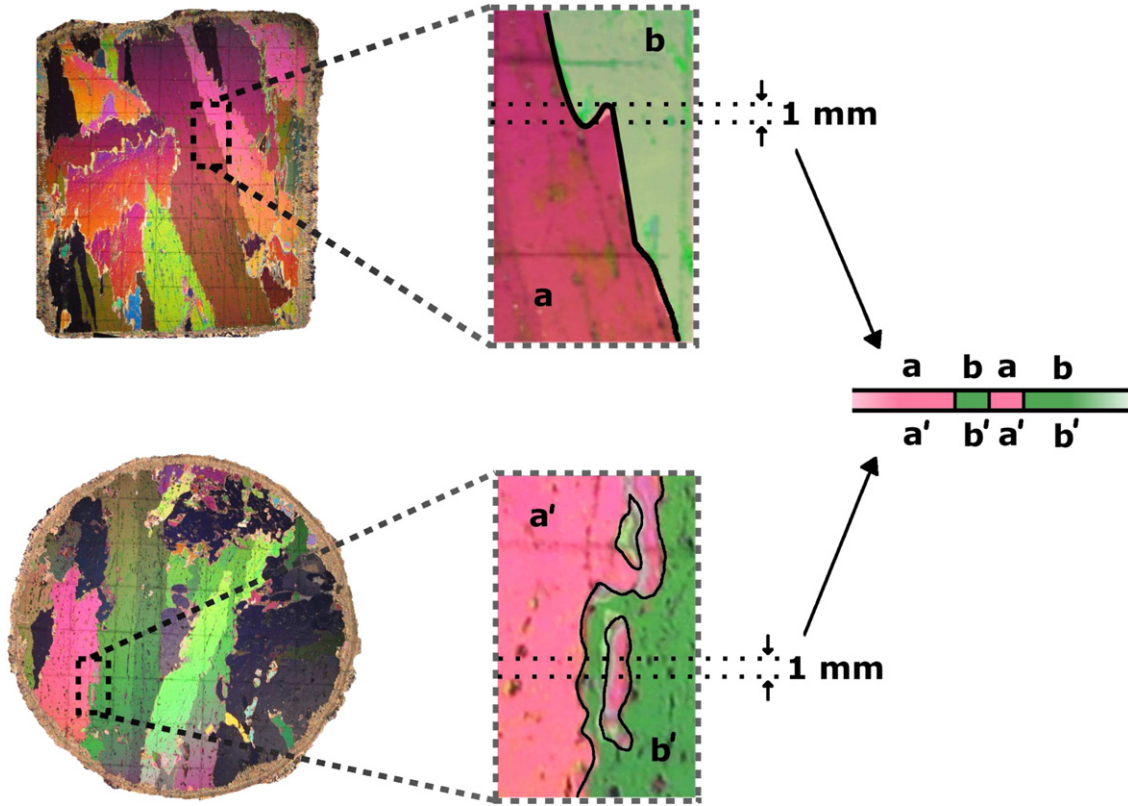


Fig. 15: Demonstration of the characteristic grain sequence for serrated sections in vertical and horizontal thin sections. The upper panel identifies such a sequence for grains a and b in a vertical section. The image is magnified (note the color of b has been artificially modified to contrast with a) and a thin slice shows the ice that would be sampled by a horizontal thin section at this depth. In the lower panel, a similar grain sequence between grains a' and b' is identified within a horizontal section, and the ice that would be sampled by a vertical section chosen at a fortuitous location is shown. On the far right is shown the grain sequence sampled by the intersecting horizontal and vertical thin sections, for both the upper and lower panels. Note that grains a and b, and a' and b', do not correspond to each other.

The proposed growth mechanism for grain boundary serration requires that grain boundary grooves, once formed, are not impinged upon by other ice crystals, i.e., the grooves remain open. The serration identified between crystals *G2* and *G3* demonstrates this behavior over an ice depth of 60 mm. For late-season ice growth rates of 10 mm/day (Purdie et al., 2006) this suggests several days of continuous growth within the groove, uninterrupted by the advection of new ice crystals. The

inferred presence of grain boundary serration throughout the entire high resolution thin sectioning study, representing an ice depth of 150 mm, suggests that either the flux of ice crystals from the ocean was small enough to have little crystallographic influence during the period that this ice grew, or that a sub-ice platelet layer existed below the groove and blocking ice crystals originating in the ocean from entering the groove.

5. Summary of results

A high resolution thin sectioning study was used to gather geometrical and crystallographic data of an assemblage of incorporate platelet ice crystals. From these data we have reconstructed individual crystals, and applied geometric fitting techniques based on ice growth kinetics and expected crystal forms.

As a method of measuring c-axis azimuth orientation, θ , ellipse fitting has demonstrated tolerable error providing it is applied to a restricted set of crystals. For instance, for crystal grains with area greater than 300 mm² and eccentricity greater than 0.87, the method is accurate to a standard deviation (parameterizing the error) of 6°, with decreasing confidence for predictions made for smaller, less elongated grains.

Reconstruction of vertical sections oriented along several planes illustrate the variety in grain shapes derived from the same crystal, all of which are valid 2-D representations of the 3-D structure. Where the angle between the basal plane and thin section plane is small the grain produced is broad and exhibits minimal elongation. Increasing the angle permits the thin section to sample more of the c-axis/basal plane growth anisotropy and consequently the grain appears elongated in the vertical direction.

3-dimensional crystal reconstructions, produced by stacking grain images vertically, are a useful tool for visualizing individual growth forms and crystal interactions within the sub-ice platelet layer. From these reconstructions we have observed pronged shaped crystals, which suggest an upward directed growth, presumably driven by heat conduction to the atmosphere. In addition, we observe two crystals whose growth impinges upon and intersects one another, which has been further correlated with observations of platelets growing freely on a cable.

Serrated grain boundaries have been identified along grains of resumed columnar ice in vertical

thin sections and their presence inferred in several of the horizontal sections. Applying geometrical arguments to the angles along these boundaries, and furnished by measurements of their c-axes, we have proposed a method of growth by layer nucleation in grain boundary grooves. This mechanism is consistent with concentric layer structures observed in images of freely growing platelets. Uninterrupted action of this mechanism over a depth in excess of 100 mm suggests that the platelet flux supplied by the ocean is significantly reduced during the period this ice grew, or that a protective sub-ice platelet layer was in place.

6. Conclusion

The preparation of thin sections of sea ice is a common method for interrogating ice structure and making inferences on the conditions of its growth. However, this mode of sampling is inherently restricted to providing a 2-dimensional slice of 3-dimensional crystal structures.

The thin sectioning study presented here therefore serves several purposes. First, production of 3-D grain boundary data has permitted a direct examination of the interactions between adjacent crystal surfaces in a sub-ice platelet layer environment. For example, the data demonstrate competitive growth between two large crystals intersecting one another over a depth of several centimeters. It has also enabled us to propose a layer nucleation mechanism for the production of serrated grain boundaries, which is present in both horizontal vertical sections.

Second, comment can be offered on the accuracy of thin section interpretation in the context of the 3-D crystal structure. For instance, we have shown that the dimensional properties of grains and grain boundaries vary as a function of vertical thin section orientation. Such limitations are a natural consequence for a 2-D rendering of 3-D data. This underscores the importance of a cautious approach to thin section analysis if misinterpretation is to be avoided.

Finally, an inferred correlation between elongation and c-axis orientation has been shown to be appropriate for large, established grains; but for smaller specimens direct measurement on a universal stage or automatic fabric analyzer is the only accurate technique. However, in the absence of the original ice samples, for instance, when analyzing historical datasets, the geometric technique may offer the only avenue for extracting crystallographic information.

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