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The microstructure of ice and its influence on mechanical properties

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Abstract

A sound knowledge of and ability to model the mechanical behavior of ice is a key element in addressing a wide range of needs of the ice research community. Continued advancement requires an understanding of the relationship between microstructure and the flow and fracture of ice under a wide range of conditions. To provide perspective on this relationship, the paper presents a description of the main microstructural types of ice and their origins, and examines current knowledge of the relationship between the microstructure and the flow and fracture of freshwater and sea ice. The influence of microstructure on the components of strain (elastic, anelastic and viscous) receives attention, as does the flaw structure of sea ice and its influence on larger-scale crack propagation. Comments are offered on the nature of the microphysical processes that underlie the viscous deformation of single crystal and polycrystalline ice. Some aspects of the microstructural changes that occur during deformation are also discussed. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The study of the mechanical properties of ice presents a great variety of challenges to the research community. The challenges stem from the vast range in physical scales of the applications (from the microphysical to the geologic), the variety of the ice types of interest (columnar and granular freshwater ice, sea ice), loading regimes that cover many orders of magnitude in strain rate, as well as a considerable range in temperature. In the mid to late 20th century, military concerns motivated many Arctic sea-ice-related research programs. Current research on the mechanical properties of ice is driven from several quarters, including climate research needs and industrial development. Sea ice studies improve modeling capabilities needed to address ice–vessel, ice–structure and ice–ice interaction problems. Studies of ice–ice interaction, and the breakup of Arctic and Antarctic sea ice support global climate research. Freshwater ice mechanics

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may be roughly divided into studies of floating ice sheets, and those concerned with glaciers. The former supports improvements in inland waterway and over-ice operations, whereas the latter focuses on understanding the mechanisms of glacier flow and model development. Offshore industrial development in northern regions has driven considerable research efforts regarding sea ice and (freshwater) iceberg interaction with various types of structures.

A common trend in each of these areas is to improve predictive models based on a mechanistic understanding of the physical processes that underlie the phenomena of interest. For most applications, this approach requires a detailed description of some or all of the physical properties (density, porosity, grain size, texture, fabric, flaw structure, and salinity in the case of sea ice) of the material in question. Thus, it is important in the development and application of such predictive models to have a thorough knowledge of the relationship between the formation process and the resulting microstructure, and of how the initial microstructure changes as a function of its thermal and straining history. In light of the focus of this special issue of the Journal, this contribution describes the microstructural characteristics of the most common forms of terrestrial ice, with emphasis on the relationship between microstructure and the mechanical properties of polycrystalline freshwater and sea ice.

A unique aspect of the study of ice is the vast range of physical scales of interest. The fundamental mechanisms of flow operate on the scale of lattice defects; optical and electromagnetic properties are influenced by defects the size of individual brine and gas inclusions; fracture processes are highly scale dependent and are influenced by subgrain features, crystallographic alignment and larger features such as brine drainage networks; and large-scale sea ice dynamics problems involve complex forcing and deformation processes that occur on the scale of hundreds of kilometers. Clearly, scale influences the level of microstructural detail required for a particular application. However, the importance of microstructural characteristics to phenomena at any scale should not be discounted out of hand. A case in point is the author's observation of a sizable thermal crack that ran for several hundred meters through a test site in aligned first-year sea ice in the Alaskan Arctic. The crack precisely followed the weak-fail path dictated by the microstructure (which had been well documented during the survey of the site), despite an abrupt change in the alignment direction. Interestingly, the alignment governed the crack path even though only the central portion of the sheet was strongly aligned.

Fortunately, it is relatively easy to produce thin sections of ice, and this has led to a relatively thorough documentation of its microstructure. However, there are important cases (deep within glaciers, floating sea ice sheets, and highly damaged ice, for example) where it is difficult to obtain meaningful optical observations. Pressure relief on deep cores gives rise to cracking; brine drainage and migration alters the properties of sea ice specimens once they are removed from a sheet; and the strain energy in damaged ice drives recrystallization which can dramatically alter the microstructure. In experimental work, it is consequently important to recognize that these processes exist, and to minimize their influence on the observations whenever possible.

Interest in global climate change is bringing to the fore an interesting and challenging class of problems associated with the mechanical behavior of sediment-laden ice, ice-rich frozen ground and rock glaciers – materials that are arguably more difficult to understand than ice alone. However, it is clear that ice is at the root of the critically important temperature dependence of these complex systems, and their behavior cannot be well understood or modeled in the absence of an adequate understanding of the mechanical properties of ice.

The following sections provide descriptions of the key microstructural features of the types of freshwater and sea ice that are of concern in current scientific and engineering research. Attention focuses on the linkage between microstructure and mechanical properties of various ice types, with emphasis on the underlying microphysical processes. Primarily for sea ice, descriptions are presented of the flaw structure and the interaction between cracks and microstructure. Microstructural changes during deformation, and general modeling considerations also receive attention.

2. Ice microstructures and their origin

The microstructural characteristics of common terrestrial ice (Ice Ih) vary widely, and depend on the conditions of formation (see Ref. [1] for a useful discussion of this topic), as well as thermal and deformation history. Fig. 1 shows thin section photographs that illustrate the microstructures of granular, columnar freshwater ice, frazil, unaligned columnar sea ice and aligned sea ice. Combinations of polycrystalline forms (e.g. alternating layers of columnar and fine-grained ice) occur as well in floating ice, and alignment may vary substantially with location and depth in a sea ice sheet [2].

When a body of standing water freezes under quiescent conditions, and a minimum number of nucleation sites are available, an initial skim can form that consists primarily of *c*-axis vertical crystals. If a sheet can establish itself from this skim, the *c*-axis vertical structure is preserved, and the resulting material (termed S1 ice) consists of very large crystals that extend through the thickness of the sheet [3]. Although low-angle boundaries can be spaced at a few cm, individual grains defined by high-angle boundaries can have much larger diameters.

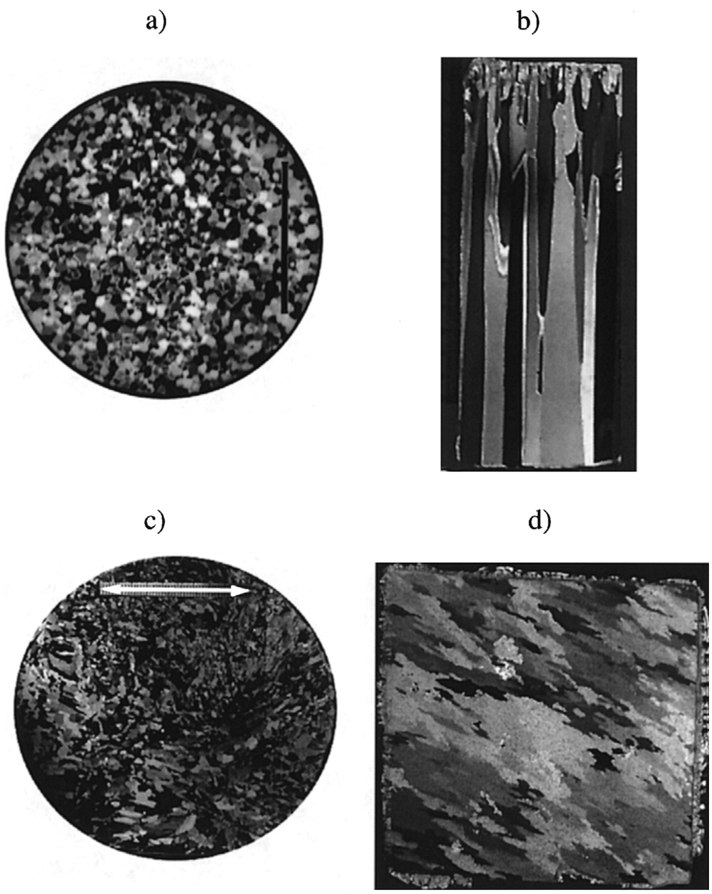

Fig. 1. Thin section photographs showing the structure of several common ice types: (a) fine-grained granular ice; (b) freshwater columnar ice, showing a fine-grained seed layer at the top, transitioning into a columnar growth with increasing grain size; (c) frazil ice; (d) aligned sea ice. Scale bars are 50 mm.

Granular or snow ice forms with the deposition and subsequent consolidation (or flooding and freezing) of snow. When the air temperature is sufficiently low, frazil ice grains nucleate in fast moving areas of rivers or in severely wind-blown standing water. These grains accumulate and consolidate to form the fine-grained structure seen in Fig. 1. Although there are some textural differences, granular and frazil ice have microstructures consisting of nominally equiaxed grains with initially random *c*-axis orientation. In contrast, a columnar-grained structure results when an ice plate forms on a standing body of water. When nucleation sites (impurities) or seed grains (snow particles) are readily available, the microstructure of the top layer of such a sheet is frequently similar to granular ice. Because the growth rate of individual crystals is fastest in a direction normal to the *c*-axis, the subsequent growth of the sheet favors grains with *c*-axes in the horizontal direction. The fact that the *c*-axes lie approximately in the horizontal plane in floating ice sheets leads to what has been termed transverse isotropy (e.g. the in-plane mechanical properties are statistically isotropic in unaligned ice, but these vary from the through-thickness properties). In columnar ice, the average grain diameter in the horizontal plane typically increases with depth because the faster growing, *c*-axis horizontal grains systematically eliminate the grains least favorably oriented for growth.

In contrast to freshwater ice, which grows with a macroscopically planar ice–water interface, sea ice grows with a dendritic interface (see Fig. 2b, and refer to Ref. [4] for details). This growth process incorporates liquid brine between regularly spaced plates and thus produces an anisotropic microstructure. The characteristic subgrain structure of sea ice is evident in the horizontal micrograph (e.g. view is in the growth direction) shown in Fig. 2c. The microstructure appears markedly different, however, in vertical thin sections taken parallel and perpendicular to the plate boundaries. The vertical micrograph in Fig. 2d gives an edge-on view of the plates (e.g. the same viewing direction as in Fig. 2b, but at higher magnification). The vertical micrograph in Fig. 2d shows a face-on view of a single plate boundary and illustrates the great variety in the size and shape of the brine inclusions at this scale. The plate boundaries are parallel to the basal planes (which are perpendicular to the *c*-axis direction), and thus further enhance the anisotropy in the mechanical properties of the individual crystals.

Significantly, since the volume of brine is a function of temperature, the microstructure of sea ice is temperature sensitive. The phase diagram for seawater indicates that the salt concentration of brine in equilibrium with ice increases as temperature decreases. Brine inclusions thus shrink in size as the temperature drops in order to maintain the proper brine salinity. This has the effect of increasing the ice phase at the expense of the brine volume. As temperature decreases, the eutectic temperature of the various salts present in natural seawater is reached and they begin to precipitate. (The eutectic point refers to the temperature at which liquid brine solidifies into two solid phases. For example, NaCl + water forms solid NaCl + ice at a temperature of −21.2°C.) Of the seven most prevalent salts in natural seawater, the first begins to precipitate at −2.2°C, and the others begin to precipitate at temperatures ranging from −8.2°C to approximately −55°C. As noted by Weeks and Ackley [4], precipitation occurs over a range, rather than at a precise temperature.

Under-ice currents have the important influence of producing a preferred *c*-axis direction (fabric) in sea ice sheets. Fig. 3 shows the range in the *c*-axis azimuth (direction in the horizontal plane) of individual crystals as a function of depth in ice from Elson Lagoon, near Barrow, Alaska (see Ref. [5]). At a depth of approximately 0.3 m, the range in azimuth narrows considerably, indicating that the crystal axes are becoming aligned in a particular direction. In this case, the *c*-axis alignment remains strong until approximately 1.4 m, at which point the growth of new, unaligned crystals disrupt the fabric. This phenomenon has now been observed in two separate years in the same area, but its cause is not understood.

It is useful to keep in mind that fabric development can be either a result of growth conditions – as in the case of sea ice – or as a result of recrystallization during deformation. Generally, fabric development via recrystallization is of concern in glaciology and thus falls primarily in the realm of freshwater ice mechanics. Fabric development during solidification is of concern in sea ice mechanics: it produces anisotropic mechanical and optical properties in the horizontal plane on a large scale.

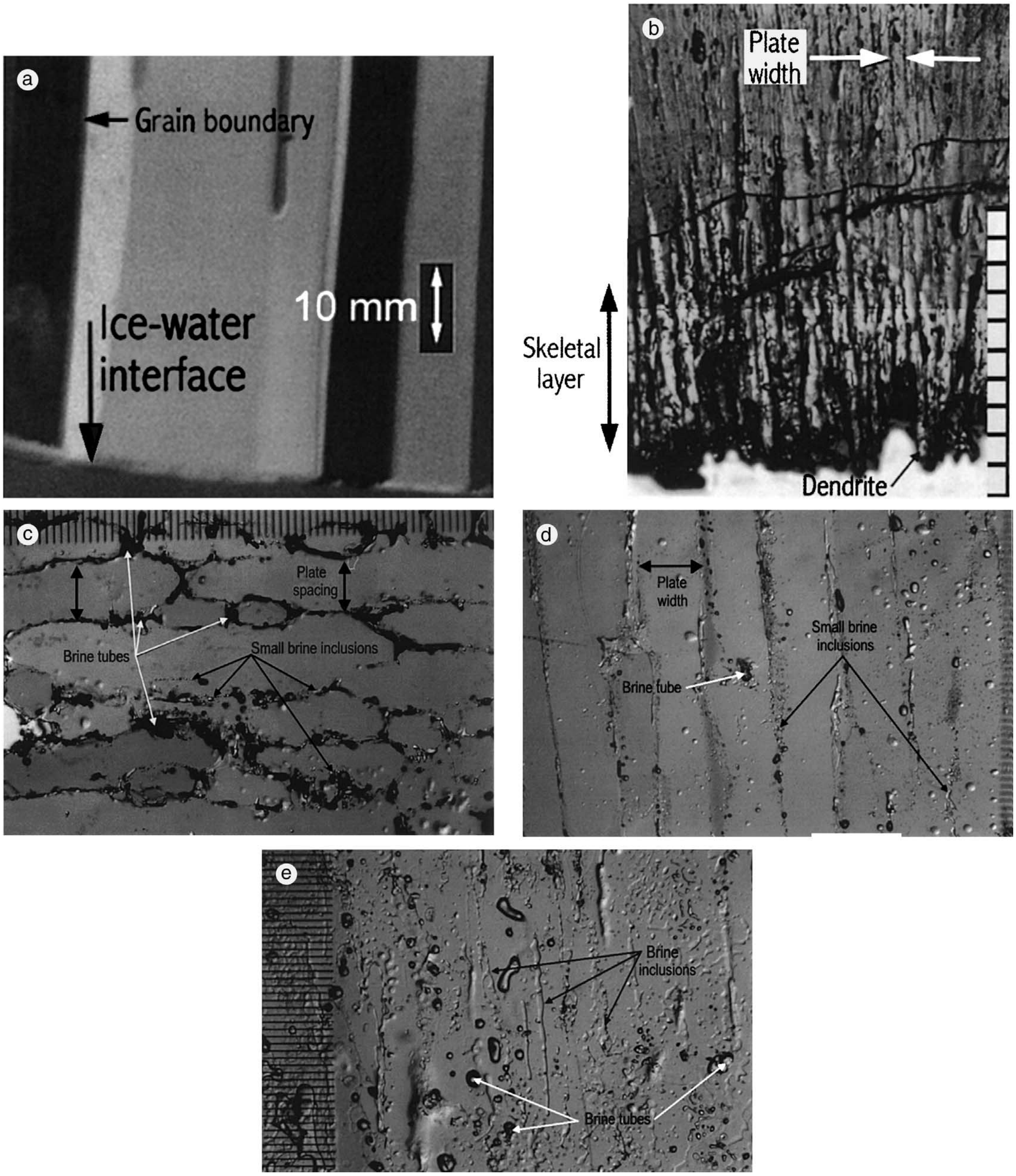

Fig. 2. The microstructure of freshwater and sea ice. (a) A vertical micrograph of freshwater columnar ice showing the grain structure and the planar ice–water interface. Note the absence of inclusions in this material. (b) A vertical micrograph of the bottom layer in sea ice, viewing the plates edge-on. Sea ice grows dendritically, trapping brine between the plates as freezing progresses. The region in which the plates have not yet grown together is known as the skeletal layer. Although the skeletal layer has been damaged somewhat in this section, individual dendrites appear as narrow, vertically oriented plates in the bottom 6–7 mm of the micrograph. The scale divisions are 1 mm. (c) Horizontal micrograph of first-year sea ice illustrating the cellular subgrain structure, showing brine inclusions and tubes. The tubes intersect the surface of the section and the brine has consequently drained. (d) Vertical micrograph of first-year sea ice viewing plates edge-on. Note how the small brine inclusions congregate on the plate boundaries in this view. (e) Vertical micrograph viewing a single plate boundary face-on (this view is orthogonal to the section shown in (d). The plate boundary is well populated with small, discrete brine inclusions, and is intersected by tubes as indicated. Scale divisions in (c)–(e) are 0.1 mm.

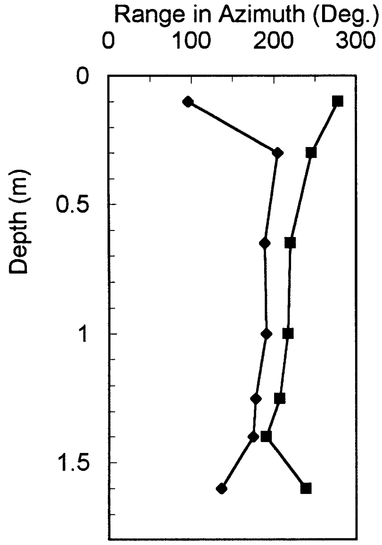

Fig. 3. Fabric as a function of depth in first-year sea ice from Elson Lagoon, near Barrow, Alaska (from Ref. [5]).

As in the case of columnar-grained (S2) freshwater ice, sea ice often consists of a fine-grained surface layer that makes a transition to a columnar-grained structure (congelation ice) with a relatively short amount of growth. Fig. 4 (part a) shows an example of this structure. A full-thickness slab of first-year sea ice appears on the left of Fig. 4 (part a). The photograph was taken under natural lighting, and the dark vertical features with diagonal side branches are brine drainage networks. The figure includes photographs of thin sections taken at the indicated depths and orientations to illustrate how the microstructure changes with depth. The thin section photographs were obtained with backlighting using crossed polarizing sheets. Fig. 4 (part b) gives an example of the structure produced when dynamic conditions prevail during freeze-up. Such conditions can produce a significant topmost layer of fine-grained ice. Uninterrupted columnar growth begins at the bottom of the irregular top layer indicated by the arrows. Unlike the growth of congelation ice, the turbulent conditions that produce frazil ice can result in the entrainment of considerable quantities of sediment in the sheet, and the dark, wavy band evident in Fig. 4 (part b) is the result of such a process. Weeks and Gow [2] found similar material in their study of Arctic sea ice. Fig. 4(c) in part b shows an extreme example of sediment entrainment that occurred in Elson Lagoon in 1999.

There are noteworthy differences in the microstructural characteristics of Arctic and Antarctic sea ice. In the Antarctic, frazil and snow ice can constitute a significant portion of the floating ice, as opposed to the columnar structure that typically dominates Arctic sea ice. Frazil ice is generated in open water and subsequently deposited underneath ice sheets or floes, and the saturation and subsequent freezing of surface snow [6] leads to the formation of a granular microstructure. In addition, examples of a microstructural type known as platelet ice have been observed in Antarctica [7,8]. This material is characterized by the growth of abnormally large single crystal platelets from the bottom of land-fast ice sheets. Platelets measuring 5 mm in thickness and up to 150 mm in diameter have been observed. These are subsequently incorporated into the growing congelation ice, giving rise to the very unusual structure seen in Fig. 5. Because of the scale of the platelets, it is very difficult to fully capture this particular microstructure with standard-sized thin sections (typically 0.1×0.1 m^2) obtained from cores, and the benefit of obtaining full-depth slabs of this material is clear from the photograph. The origin of this material is the topic of ongoing research [9].

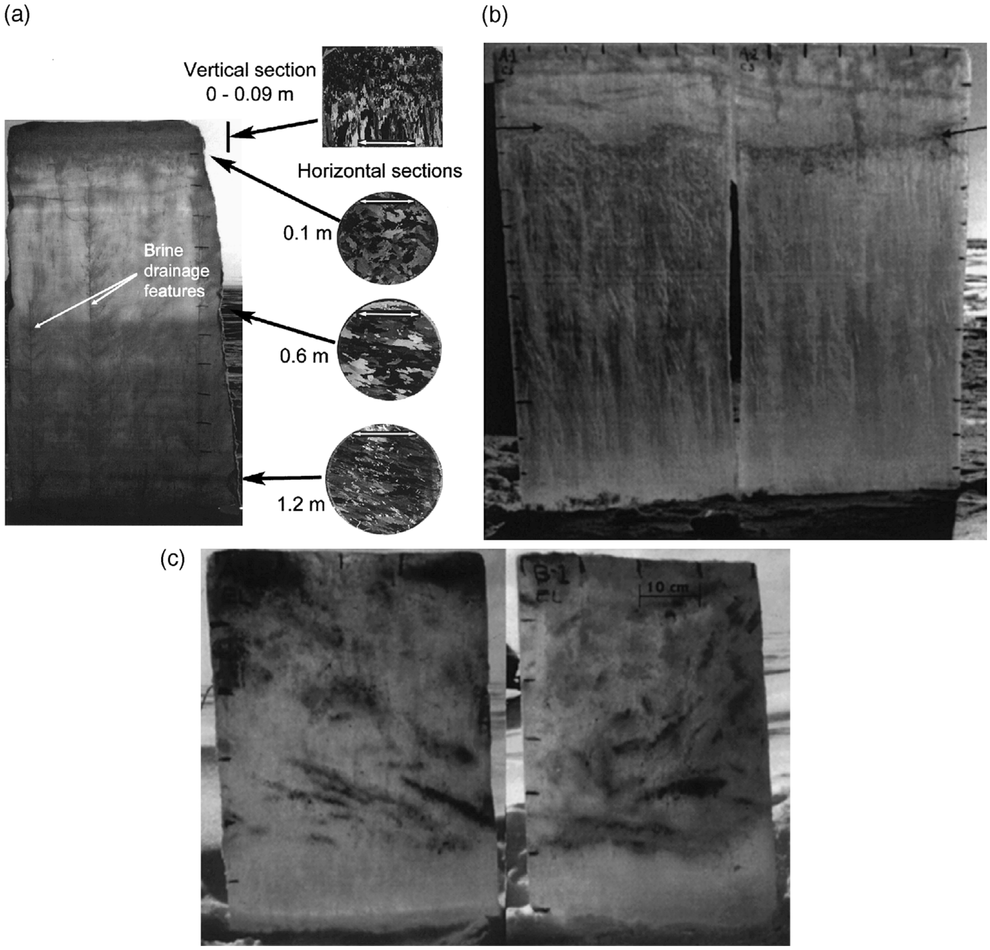

Fig. 4. Part a: Full-thickness slab of first-year sea ice retrieved from Elson Lagoon (see Ref. [5], for a description of the methods used to obtain the slab). Photographs of one vertical and three horizontal thin sections are shown to illustrate the microstructural changes with depth. Note the granular upper layer followed by continuous columnar (sometimes referred to as congelation) ice. Part b: Full-thickness slabs of first-year sea ice retrieved from Elson Lagoon in March 1993 (see Ref. [5], for a description of the methods used to obtain the slab) and the Chukchi Sea. (a) Photographs of one vertical and three horizontal thin sections are shown to illustrate the microstructural changes with depth. Note the granular upper layer followed by continuous columnar (sometimes referred to as congelation) ice. (b) Photograph of adjacent slabs from the Chukchi Sea, May 1999. The dark band between 0.2 and 0.3 m from the top of the sheet is caused by entrained sediments. (c) Photograph of slabs from Elson Lagoon in November 1999, showing an extensive amount of entrained sediments. Marker spacing is 0.1 m.

2.1. Comments on laboratory-prepared specimens [1] and field cores

It is common for experimental work to employ laboratory-prepared specimens, either because of a desire to carefully control the physical properties of the material or because of the expense and difficulty of obtaining suitable field cores.

[1] The term "artificial ice" has occasionally been used to describe water–ice specimens frozen in the laboratory rather than in nature. However, the term "laboratory prepared" is preferable since the resulting material is in fact ice, and not a substitute, as the term "artificial" implies.

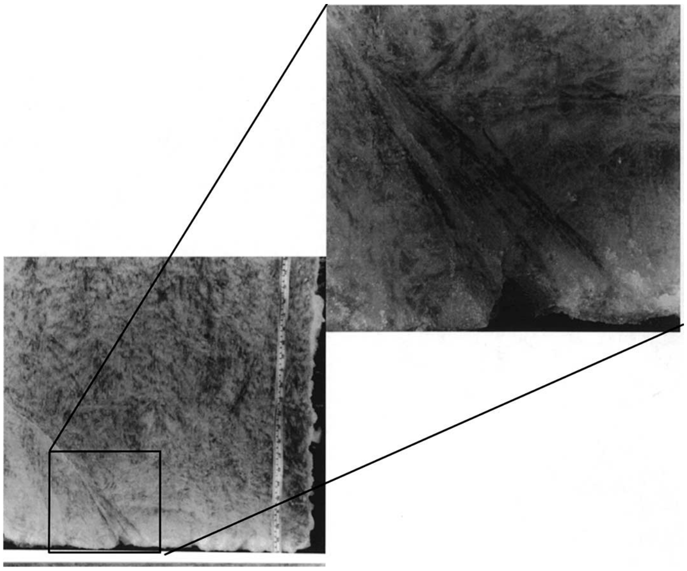

Fig. 5. A vertically oriented slab of first-year sea ice obtained in McMurdo Sound, Antarctica, illustrating platelet ice growth. The lighting and background color make the platelets appear as thin, dark features, which are shown at higher magnification on the right.

Although the naturally occurring ice is polycrystalline, a good deal of experimental work has been conducted on single crystals in an effort to understand the material on a fundamental level. Large grain sized material has been harvested from glaciers and relatively large crystals can result when lake ice forms under quiescent conditions to produce macrocrystalline, *c*-axis vertical material as described above. It has been the author's experience that low-angle grain boundaries in naturally occurring S1 ice make this material unacceptable for laboratory mechanical properties experiments. Most researchers opt to grow single crystal stock in the laboratory, from which individual specimens with specific orientations can be obtained (see for example, Ref. [10]). The 50-mm-diameter specimen shown in Fig. 6 was cut from a very large single crystal that was grown in the laboratory. The parent crystal was propagated from a plate-shaped seed grain that was originally grown from laboratory-prepared S1 ice as described in Ref. [11]. The surface ledges in this post-test photograph result from shear deformation along basal planes that were oriented at 45° to the loading direction.

Although work on the mechanical properties of single crystals has become more refined, a key problem turns out to be a lack of control over the grown-in dislocation density in the crystals. Fig. 7 shows the cyclic loading response of three single crystal specimens that have not previously been strained, and that are oriented with their basal planes at 45° to the loading direction. The specimens were cut from the same laboratory-prepared parent crystal and subjected to identical handling procedures (cut from the parent block using a band saw and brought to final diameter using the warm die extrusion technique Cole [11]). However, they display remarkably different cyclic loading responses as a result of differences in their initial dislocation densities. (The loading conditions are such that existing dislocations move under the sinusoidally varying stress, but no new dislocations are generated.) Since the inelastic deformation is proportional to the dislocation density, the specimen with a high initial dislocation density will exhibit greater losses during cyclic loading, and exhibit faster creep strain rates than one with a low dislocation density for a given stress. The experimental observations indicate that the dislocation density of single crystal specimens should be assessed prior to their use in a mechanical properties experiment.

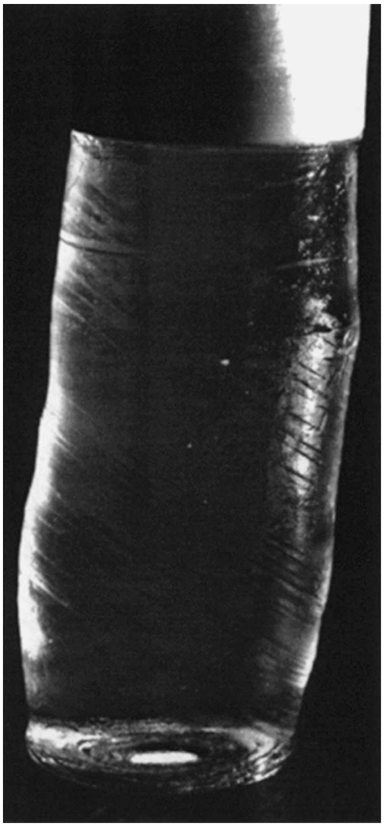

Fig. 6. Photograph of an ice single crystal after straining. This specimen was oriented with the basal planes at 45° to the loading direction (easy glide orientation), and the slip bands are evident on the specimen surface.

Similar problems have not been encountered with columnar-grained ice specimens, which presumably exhibit a spatially averaged response. The grain size of laboratory-prepared columnar ice can be controlled somewhat through the size of the seed grains and the depth at which the specimens are obtained. Smith and Schulson [12] describe a sampling technique for obtaining microstructurally similar columnar ice specimens. It calls for taking a series of relatively thin ($\approx$25 mm) plate-shaped specimens along the growth direction. Although the grain size inevitably increases slightly, adjacent specimens have very similar microstructures with respect to grain shape and orientation. This method provides a set of nearly replicate specimens for investigations of microstructural effects on deformation processes.

Because of the macroscopically planar freezing front, it is a relatively simple matter to grow bubble-free single crystal and columnar ice specimens in the laboratory. However, the preparation of suitable granular ice specimens for laboratory experiments presents a number of difficulties, primarily associated with minimizing or eliminating gas porosity. Such material is usually grown from an initially isothermal mixture of individual ice grains and water. This circumstance leads to a very convoluted freezing front that tends to isolate pockets of water before the entire mass freezes. Bubbles typically form due to the rejection of dissolved gas when these pockets freeze. Methods have been developed to overcome these difficulties, and the reader is referred to Refs. [13,14] for details. More recently, Goldsby and Kohlstedt [15] presented a method of sintering ice powders to form very fine-grained ($3 \leqslant d \leqslant 90$ μm) specimens for mechanical properties studies. Extending experimental observations to such low grain sizes should provide some

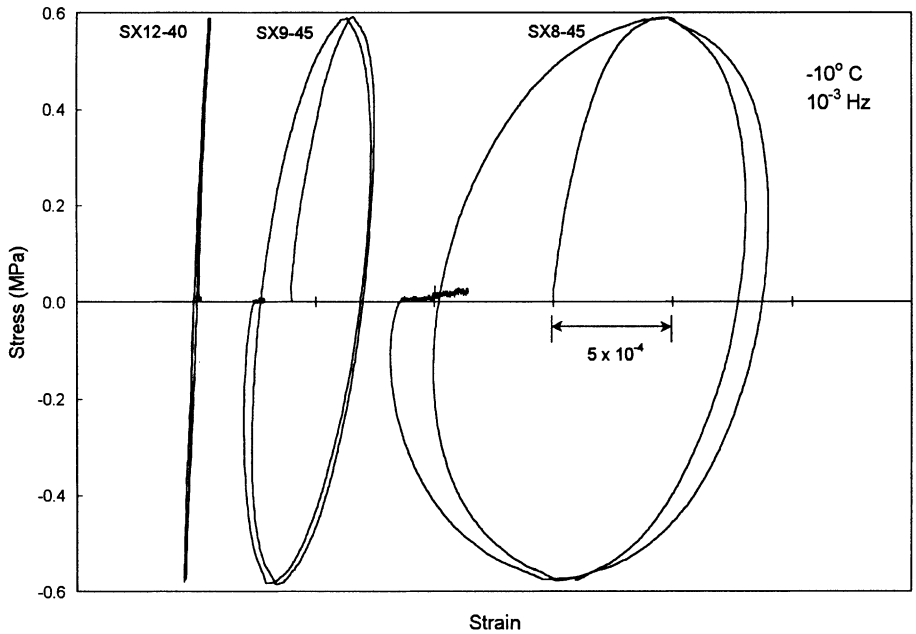

Fig. 7. Examples of the cyclic loading response of ice single crystals oriented for easy glide. The significant differences in the hysteresis loop areas give evidence of corresponding variations in the grown-in dislocation density.

useful insight regarding deformation mechanisms and grain size effects. However, sintering under high stress levels raises concerns about the initial dislocation density of this material. As noted in the comments on single crystals, variations in the initial dislocation density can have a profound effect on the mechanical properties and this aspect of the preparation method of Goldsby and Kohlstedt [15] bears scrutiny.

Turning attention to sea ice, it is relatively straightforward to produce material with an acceptable sea ice microstructure in the laboratory. However, since the advancing ice–water interface rejects most of the dissolved salt, care must be taken to avoid an excessive increase in the salinity of the water if freezing is conducted in relatively small vessels. Since sea ice contains a significant amount of liquid brine, its drainage and the metamorphosis of the associated flaw structure once sea ice is removed from its in situ conditions is a factor for both laboratory-prepared specimens and field cores. There is an advantage to laboratory-prepared specimens in this regard because they can typically be tested soon after their formation, thus avoiding the microstructural changes associated with the transportation and storage of field cores. (Refer to Ref. [16] for a detailed analysis of brine drainage during the shipment of sea ice cores.) Fig. 8 shows horizontal micrographs of first-year Arctic sea ice taken within hours of its removal from an ice sheet and, after shipping, up to several months of storage below the eutectic temperature, and warmup to a test temperature of $-10°C$. The figure shows the dramatic changes in the flaw structure that result from this time–temperature history. On average, this history produced a drop in specimen salinity of approximately 20% (≈ 5 to ≈ 4 ppt). Although much can be gained from laboratory studies of this material, the fact that the physical properties of harvested ice differ from the in situ properties must be recognized. This concern is avoided by the use of more sophisticated in situ experiments in recent years [17–20].

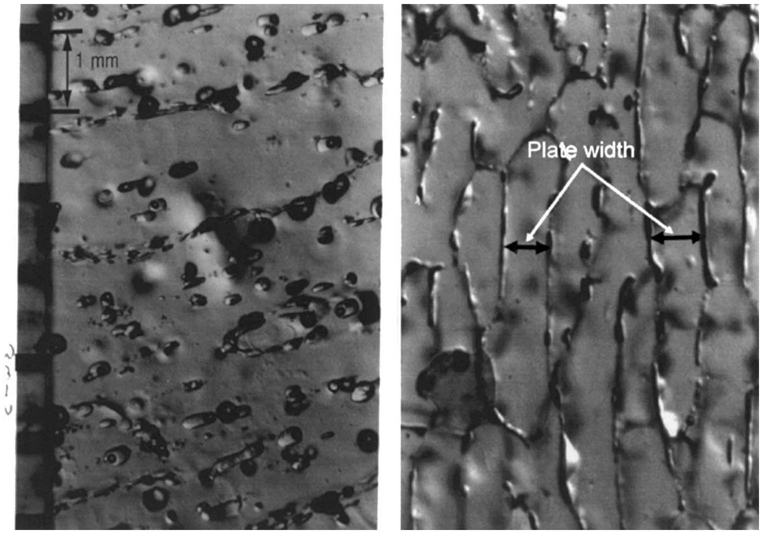

Fig. 8. Horizontal micrographs illustrating the effect of time–temperature history on the flaw structure of first-year sea ice. The micrograph on the right was obtained shortly after the specimen's removal from a young ice sheet. The voids (dark regions) lying along the plate boundaries are brine filled when the ice is in situ. The micrograph on the left shows material from the same sheet after shipment and storage as described in the text. The magnification for both images is ×16, and the scale markings are 1 mm.

3. Relationships between physical and mechanical properties

The following sections examine several aspects of the influence of microstructure on the mechanical properties of ice. An important theme is that deviations from purely random grain orientations in polycrystalline ice give rise to anisotropy in mechanical behavior. Fabric produces a very strong anisotropy in the anelastic and viscous components of strain when the loading conditions result in the generation or movement of dislocations. Equally important is the concept that the dislocation density (the total length of dislocation lines per unit volume of material) on the basal plane is generally not a fixed quantity. The initial number of dislocations depends on the ice type and growth conditions, and further variations can occur as a function of time–temperature–strain history. Typically, the dislocation density increases to a stress-dependent value over the initial 0.005–0.01 of strain. Because dislocation density so strongly influences the overall material behavior, it is critical in the writer's view that this aspect of ice behavior be adequately captured in any detailed constitutive model.

3.1. Comments on single crystal behavior

The elastic properties [21,22] and many aspects of the inelastic properties of single crystals have been reasonably well understood for some time. As with other crystalline solids, it has generally been believed that knowledge of the deformation of ice single crystals is essential to understanding polycrystalline ice behavior. This certainly appears to be true at least for the elastic properties: the unrelaxed elastic behavior of polycrystals is well predicted from the elastic constants of single crystals. However, the picture becomes less clear when inelastic deformation occurs. Additionally, there are important differences between the flow behavior of polycrystalline ice and single crystals that present difficulties with regard to expressing polycrystalline flow characteristics in terms of single crystal behavior. When subjected to creep loading in the ductile regime (e.g. no microcracking occurs), single crystals usually show an increasing creep rate until a nominally constant strain rate is achieved after several % strain [23]. Previously unstrained polycrystals, on the other hand, typically exhibit a decreasing creep rate during the first 0.01 strain, followed by a period of increasing rate. Comparison of the flow behavior of single crystals and polycrystals is inherently problematic because the applied stress is typically related to the creep rate observed at relatively high strains for the single crystals, and to the minimum creep rate (observed at approximately 0.01 strain) for the polycrystals.

The flow of ice is usually analyzed in terms of the applied stress to a power (n) and the resulting strain rate (a so-called power law relationship). The value of the exponent n receives a considerable amount of attention since it is related to the underlying mechanisms of deformation.

As noted previously, given a resolved shear stress on the basal planes, ice strongly prefers to deform by basal dislocation glide. Shearing is distributed throughout the single crystal specimen seen in Fig. 6 (with the exception of the planes that intersect the ends of the specimens), which has been subjected to compressive creep straining in excess of 0.05. In single crystals, the basal dislocations needed to support the shear deformation can be produced at a free surface or internally either by Frank–Read sources or the cross-slip mechanism described by Shearwood and Whitworth [24]. As observed directly in the work of Liu et al. [10], dislocations in polycrystals are generated primarily at stress concentrations associated with grain boundaries. There is no guarantee that grain boundary source mechanisms in polycrystals will exhibit the same stress, strain and temperature dependencies as the source mechanisms operating in single crystals. In fact, the experimental observation that single crystals and polycrystalline ice exhibit different power law exponents indicates that fundamental differences exist.

For previously unstrained ice, the flow of single crystals follows an $n \approx 2$ power law under conditions that usually lead to an $n \approx 3$ power law in polycrystalline ice. This difference is difficult to explain if a grain in a polycrystal deforms essentially as a single crystal with geometric constraints. However, the difference between single- and polycrystalline flow can be explained if the process of dislocation production in polycrystals has a stronger stress dependence than in single crystals. On this interpretation, there is a difference in the power law exponent because the number of dislocations produced by grain boundary sources in polycrystals varies with the square of the resolved shear stress, whereas the operative sources in single crystals apparently have an approximately linear stress dependence. This interpretation requires that the flow rate be proportional to the product of the number of dislocations and their velocity, and that the velocity in turn is a linear function of the resolved shear stress acting on the basal planes. Whitworth [25] summarizes experimental observations that indicate a linear relationship between dislocation velocity and applied stress. The recent finding of Cole and Durell [26] support the glide-based theory of flow and show that the dislocation density is proportional to stress to the second power in polycrystalline ice. Comprehensive experimental evidence of the precise stress dependency of the dislocation density in single crystals, however, is currently lacking.

3.2. Polycrystalline ice

As described above, granular ice consists of nominally equidimensional grains, and is typical of glaciers and the uppermost layer of ice sheets. This material is usually characterized by its average grain size, grain orientation, grain morphology and bulk density. The properties of granular ice are statistically isotropic when the grains are randomly oriented, but recrystallization during creep deformation can produce a preferred c-axis orientation that results in anisotropic mechanical properties. Grain growth and fabric development increase with depth in glaciers, and the observations of Kohnen and Gow [27] illustrate the relationship between acoustic velocity (and thus modulus) and fabric development with depth in Antarctic glacier ice. It has been demonstrated with experiments that the deformational (or syntechtonic) recrystallization that occurs during glacier flow leads to an equilibrium grain size [28] that is a function of temperature and stress level. Thus, while the mechanical behavior at short times (and low strains) may be influenced by the initial microstructure, the microstructure at long times (and high strains) is apparently governed by the deformation process.

The mechanical properties of granular ice have been studied in the laboratory largely in support of glaciological research, which focuses on longer-term deformation under relatively low applied stresses (see, for example, Refs. [29–31]). However, the deformation and failure of this type of ice at high rates of loading and under high confinement are important in engineering problems associated with iceberg–structure interaction. In recent years, a considerable effort has focused on understanding the microstructure that evolves during such interaction and the resulting effects on constitutive behavior [32–37]. Among the difficulties presented by such loading conditions are tracking rapid changes in the microstructure that occur under high pressure and understanding the effects of high damage levels on the constitutive behavior.

Extensive efforts have focused on documenting the evolution of fabric during creep deformation, and on understanding the extent to which the mechanical properties are influenced by the fabric. However, although experimental work has laid a foundation for an understanding of fabric development during straining, it appears that a quantitative theory and a related physically based model for this important process are lacking.

The bulk of floating ice has a columnar structure, and a great number of laboratory and field experiments have been carried out on this type of ice. As noted above, the microstructure of columnar ice gives rise to a strong anisotropy in many of the mechanical properties. Consideration of columnar ice is frequently divided into the areas of freshwater and sea ice. Since freshwater columnar ice does not develop a preferred *c*-axis direction in the horizontal plane, its mechanical properties are not expected to vary as a function of direction in the plane of the sheet. On the other hand, *c*-axis alignment is common in sea ice, giving rise to a potentially strong anisotropy (depending on the degree of alignment) in the deformation and fracture characteristics in the horizontal plane.

3.3. Grain size and grain boundaries

Grain boundaries are important features in polycrystalline ice: they act as sources and sinks for dislocations, they give rise to stress concentrations that lead to crack nucleation, and they are a source of anelastic relaxation. Experiments have shown that grain size significantly influences the uniaxial tensile strength [38], to a lesser extent the compressive strength [39,40], the flexural strength [41], the size distribution of microcracks [42] and internal friction [43]. Particularly for the case of freshwater ice undergoing microfracturing, grain size has proven to be a key microstructural characteristic [44] with regard to the development of failure criteria. Grain size has also been observed to influence the ductile to brittle transition [45].

X-ray topography [10] has indicated that triple points and ledges in grain boundaries are important sources of dislocations in ice, and the dislocations in turn play a vital role in inelastic deformation. Grain boundaries have long been associated with microcracking [42,46–48]. Although constrained elastically by neighboring grains and ledges, grain boundaries can slide, and this gives rise to stress concentrations at the obstacles to shear displacement. As pointed out in Ref. [49], the anelastic strain associated with pure grain boundary sliding (as evidenced by the height of the grain boundary internal friction peak) in undeformed polycrystals is remarkably constant for widely varying ice types and microstructures, as indicated in Fig. 9a. The experimental data show that the height of the internal friction peaks (and thus the relative strengths of the relaxation process) is reasonably consistent for freshwater granular ice, columnar sea ice and freshwater ice (when the latter two types are loaded normal to the growth direction). Note that there is essentially no internal friction peak for the freshwater columnar-grained specimen with an angle of 45° between the loading direction and the long axis of the grains. Because of the lack of triple points to hinder the grain boundary sliding motion in this orientation, the internal elastic stress fields necessary to produce the

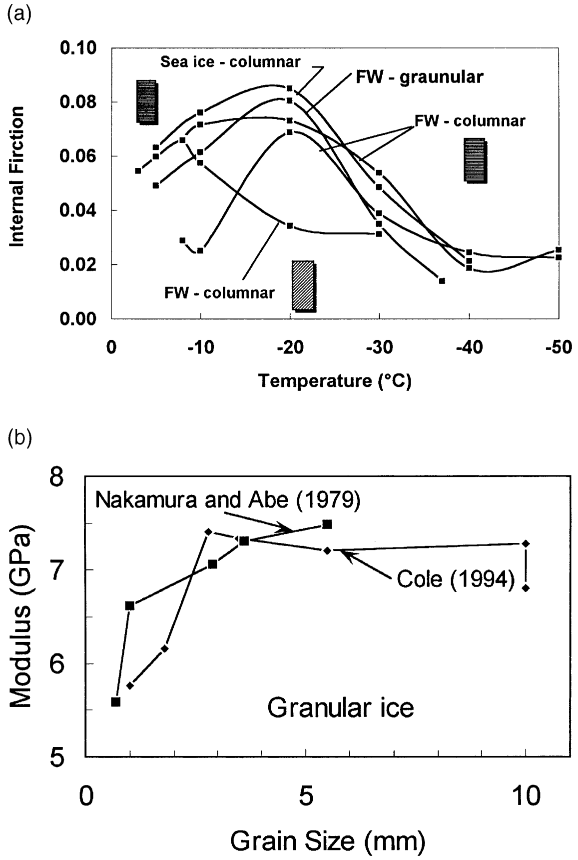

Fig. 9. Grain boundary effects in ice. (a) Grain boundary internal friction peaks in undeformed polycrystals of granular freshwater ice and columnar freshwater and sea ice. The columnar ice was oriented with the long dimension of the grains either perpendicular or at 45° to the loading direction, as indicated by the diagrams in the figure. (b) The effective modulus of granular freshwater ice observed under cyclic loading as a function of grain size.

internal friction peak are absent. Fig. 9b shows the grain size effect in the effective modulus of laboratory-prepared granular freshwater ice [49], and glacier cores [50] observed under cyclic loading. Note the decrease evident for grain sizes below about 3 mm. Interestingly, the internal friction experiments of Tatibouet et al. [43] indicated that creep deformation suppresses grain boundary sliding. Under the conditions of those experiments, creep deformation induced grain boundary distortions to such an extent that the free sliding distance along boundary facets decreased to the point of eliminating the grain boundary internal friction peak. This indicates the need to consider strain history when assessing the potential of a particular microstructure to develop cracks.

Although grain boundary sliding is sometimes identified as an important deformation mechanism in polycrystalline ice, the contribution of pure grain boundary sliding (with only elastic accommodation) to overall straining in polycrystals is roughly equal to the elastic strain and thus relatively small. However, larger strains can result when grain boundary sliding is part of a process that involves an additional accommodation mechanism (intragranular slip or diffusion, for example). It should be noted that boundary sliding is not necessarily the rate-controlling mechanism in a process (such as creep) that exhibits a grain size dependence. Extensive grain boundary sliding might be expected in very fine-grained material – when the grain size is less than the typical ledge spacing, and the facets are microscopically smooth and free to slide extensively.

4. Flaw structures

Attention here is confined to features that develop as a result of microphysical processes that occur during growth, rather than large-scale flaws that result from subsequent thermal or dynamic effects.

4.1. Gas and brine porosity

Gas-filled bubbles are the predominant inclusion in freshwater ice, and Gow and Langston [51] present a variety of examples of gas porosity distributions in freshwater lake ice. Sea ice, on the other hand, is densely populated by relatively small-scale inclusions of liquid brine (see Fig. 1), as well as gas inclusions. The brine-filled inclusions in particular congregate along the plate boundaries of the subgrain structure described above, and have a dramatic effect on many physical, mechanical and electromagnetic properties. The brine gives rise to temperature-dependent effects not only on the elastic behavior (because the brine porosity changes with temperature), but also the viscous and anelastic behavior through its apparent influence over the dislocation density. Although brine volume (v_b) effects have traditionally been addressed empirically through a factor such as $(v_b)^{-1/2}$ in sea ice mechanics, recent efforts [52] incorporate brine porosity more directly in terms of its influence on each component of deformation.

4.2. Brine drainage features

Fig. 10 shows examples of brine drainage networks in first-year ice. An initial array of these features form as the ice sheet grows (primary drainage channels), with spacing usually in the range of 0.10–0.15 m. The scattering of light by gas inclusions in the main vertical channel and its side branches make these features visible. These features are typically filled with very fine-grained ice and are relatively impermeable to the downward flow of brine or the intrusion of seawater from below until spring warmup. These features have been of interest for some time [53–55] and play an important role in the development and evolution of the physical and mechanical properties of sea ice sheets. As indicated in Ref. [5], however, these well-formed brine drainage features having a distinct central stem with an array of side branches are not universally observed.

Increased brine mobility during warmup can cause these channels to open up, and also gives rise to another set of open channels (secondary drainage channels) that can be rather closely spaced (Cole and Shapiro [5] reported spacing as close as 0.05 m for these features). Fig. 11 shows a micrograph taken through a secondary drainage channel. The line of sight for this micrograph is in the growth direction. Note that imbedded in the large-grained congelation ice, there are two clear holes surrounded by fine-grained ice. Current thoughts are that these channels meander laterally as a result of thermal fluctuations and leave the fine-grained recrystallized ice in their wake.

Because the brine inclusions are not stable, and floating ice exists at high homologous temperatures, the flaw structure of sea ice undergoes a virtually constant metamorphosis, with the most dramatic changes occurring when the sheet warms up at the onset of melt season. The microstructure of saline ice has been shown in the laboratory to have an influence on the paths of small-scale brine drainage features [56]. However, apart from the formation of the characteristic subgrain structure, field observations [5] give no indication of a systematic relationship between the microstructure and larger-scale features such as brine

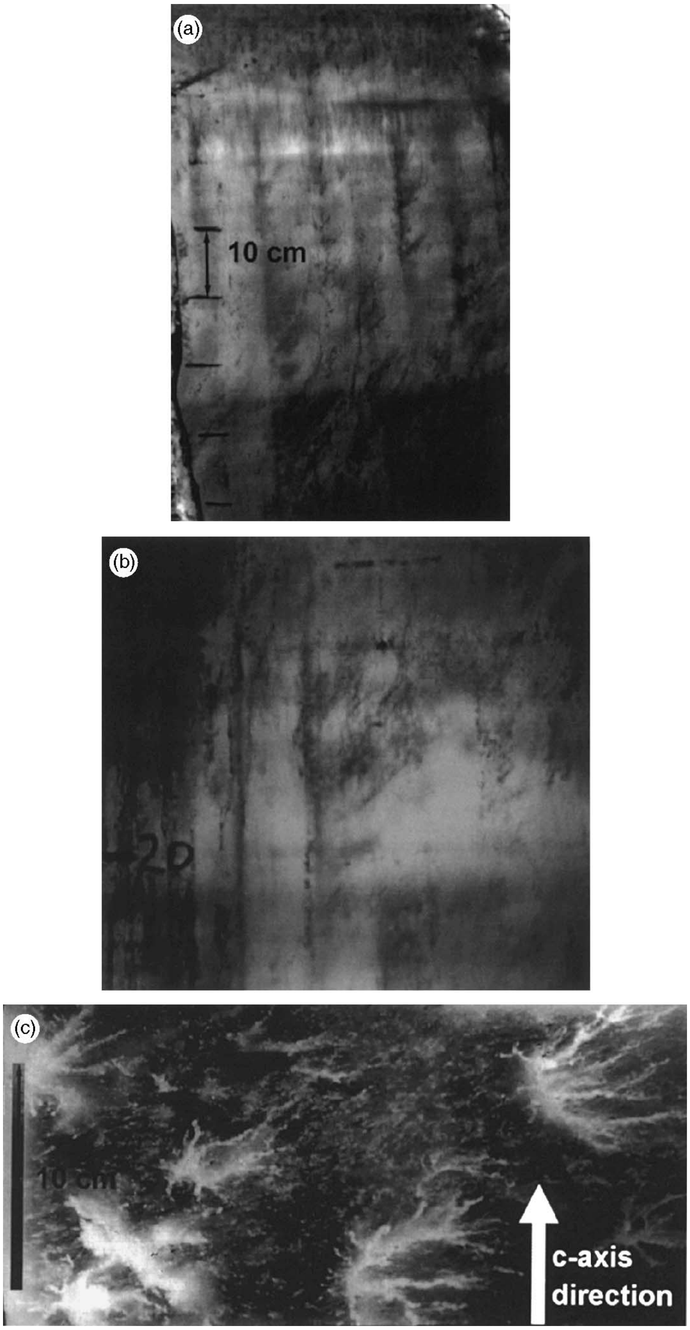

Fig. 10. Examples of brine drainage networks in first-year ice. (a) Vertical slab under backlighting. Drainage networks appear as dark vertical features with oblique side branches. (b) Magnified view of the type of features seen in (a) under backlighting. Abrupt changes in the drainage features did not appear to be linked with variations in the microstructure. (c) Horizontal slab showing a cross-section of several drainage networks. This section is obliquely lit, causing the drainage features to appear as light regions. Scale markings are spaced at 0.1 m.

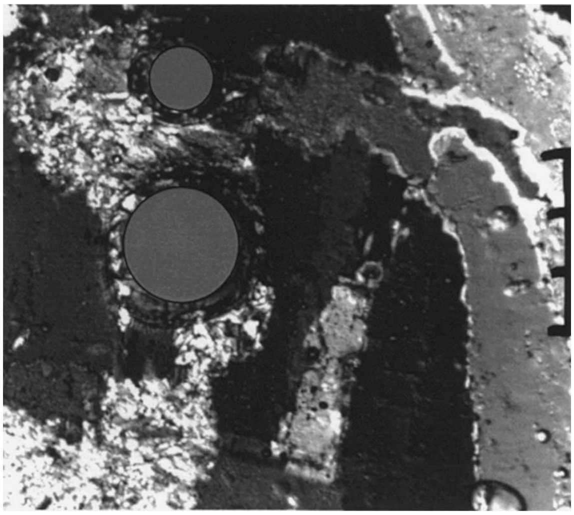

Fig. 11. Horizontal micrograph taken through a secondary drainage channel. The line of sight coincides with the growth direction. This section contains two open drainage channels (highlighted for emphasis) and a region of very fine-grained ice imbedded in the larger-grained congelation ice. The scale divisions are 1 mm.

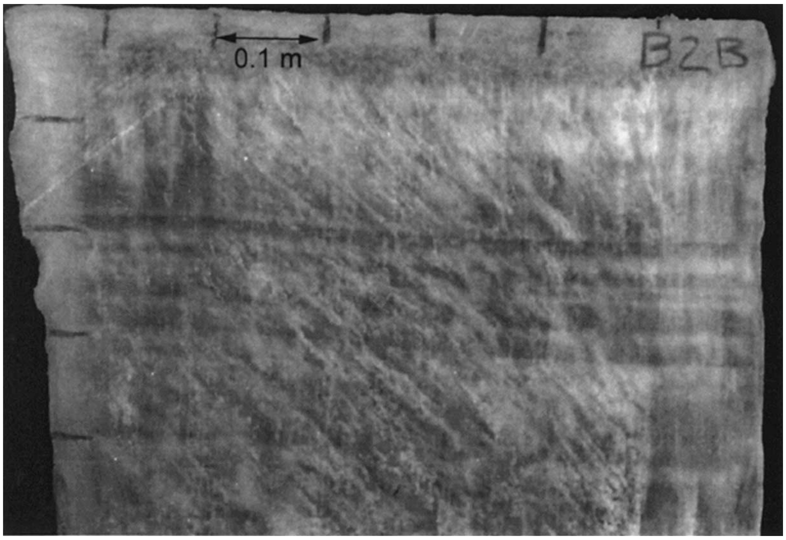

Fig. 12. A region of diagonal brine drainage features observed in first-year ice in the Chukchi Sea. The boundaries of this region did not correspond to any discernable crystallographic changes [5–7].

drainage networks or the drainage tubes that develop during spring warmup. Fig. 12 shows an example of the apparent lack of correspondence between brine drainage features and crystallography. The abrupt change in the defect structure evident in the figure is not associated with any discernable crystallographic feature (such as a high-angle grain boundary).

5. The influence of microstructure on the components of strain

Deformation processes in ice are typically modeled in terms of elastic, anelastic (time-dependent but recoverable) and viscous (permanent) contributions, and microstructure has an influence on each of these components. The following sections briefly consider the influence of microstructure on each of the components of strain in polycrystalline material.

5.1. Elastic

Sinha [57] and Cole et al. [58] accounted for the effects of fabric on the pure elastic modulus with an expression that integrates the temperature-dependent single crystal modulus values over the grain orientation distribution. Cole [52] illustrated that the predictions of this approach are in agreement with moduli derived from ultrasonic velocity measurements on glacier cores with a known fabric, and with laboratory measurements on cores of aligned sea ice whose fabric had been thoroughly documented. It is worth emphasizing that relaxation effects make it difficult to precisely measure purely elastic behavior in ice polycrystals by quasistatic methods (as opposed to ultrasonic methods). For example, at −10°C, the grain boundary sliding mechanism will be nearly fully engaged within 1 s, giving rise to a modulus defect of typically 10% (or more for small grain sizes). This relaxation effect can be avoided by either testing at much lower temperatures, or, as in the case of ultrasonic measurements, at high rates and low stress or strain amplitudes.

An analysis of the available data for sea ice below the eutectic temperature [52] indicated that gas porosity (v_a) effects on the pure elastic modulus are well represented by an expression of the form $(1 - 3v_a)$, which applies to the case of non-interacting voids [59] with a Poisson ratio of 1/3.

5.2. Anelastic

The anelastic (or delayed elastic) response of ice has been studied in the laboratory for some time [60–63]. The two primary processes responsible for the anelastic behavior (time-dependent but recoverable strain) of polycrystalline ice are a dislocation relaxation and grain boundary relaxation [63], and most attention has been paid to the dislocation relaxation. The strength (e.g. the maximum strain associated with the mechanism) of the dislocation relaxation depends on the number of participating dislocations (effective dislocation density) and can vary from essentially zero for very low dislocation densities (or for orientations that preclude basal slip) to 8–10 times the elastic strain. Thus, when this anelastic relaxation mechanism is fully engaged, it reduces the elastic modulus by a factor of approximately 10. In contrast, the modulus reduction associated with pure grain boundary sliding is 10–20% for grain sizes typically found in nature.

Since basal dislocations, when present, are the most important contributors to anelastic relaxation in ice, the total strain associated with this mechanism is a strong function of the resolved shear stress on the basal planes. For this reason, the anelastic component of strain varies significantly with loading direction in ice types that are not statistically isotropic. Since the number of dislocations typically increases during straining, the anelastic strain level can increase dramatically with accumulated viscous strain, and a subsequent section addresses this topic in detail.

With regard to microstructural effects, results presented by Cole [62] indicate that dislocation-based anelastic straining is not a function of grain size in freshwater granular ice examined under creep (ductile) loading conditions. However, grain boundary anelasticity increases as grain size decreases.

5.3. Viscous

Over much of the range of interest in engineering applications, ice exhibits power law behavior with $n = 3$–4, with an activation energy usually taken as 0.7 eV. Viscous straining typically becomes significant after $\approx 10^3$ s under load, and as discussed in a subsequent section, the viscous strain rate is not necessarily constant from its onset, but rather depends on the effective mobile dislocation density. The power law breaks down near the ductile-to-brittle transition (typically between strain rates of 10^{-4} and 10^{-3} s^{-1}, depending on the material and temperature) owing to an increasing crack population. A transition to linear ($n = 1$) flow occurs below a stress of approximately 0.1 MPa for freshwater ice, and there is evidence of a somewhat higher threshold stress for sea ice [64].

A quantitative understanding of the effects of microstructure on viscous straining in polycrystalline ice requires knowledge of the rate-controlling process. Although there has been a long-running debate about the microphysical mechanism(s) of ice creep [65,66], there seems to be general agreement that dislocation motion figures prominently into the flow process. The central debate is whether the viscous strain rate is controlled by the unusually high drag that basal dislocations experience (glide control), by the rate at which they can escape obstacles via diffusion (climb control), or by a balance of deformation on hard and soft slip systems. As described in Section 7.1, some recent findings favor the glide-controlled explanation.

The viscous strain rate is a strong function of orientation in single crystals [23] and of fabric in polycrystals. Although non-basal slip has been observed, the strain rates for a given applied stress are approximately 60 times slower than for basal slip, so basal slip is by far the preferred method of deformation. Since non-basal slip contributes little to the overall straining, its importance is most likely the production of basal dislocations via the cross-slip mechanism described by Shearwood and Whitworth [24]. As described in a subsequent section, the relationship between fabric and the viscous strain rate is reasonably well described by using the resolved shear stress on the basal planes.

6. Microstructure and fracture

Well-controlled in situ experiments on sea ice and S1 freshwater ice provide clear evidence of the important influence that microstructural characteristics exert over larger-scale fracture processes. Exceptionally low in situ crack velocities (values as low as 10 m s^{-1} have been reported by Dempsey et al. [19]) and the existence of size effect regimes in the fracture strength of sea ice are among the consequences of the strong interaction between cracks and microstructure, and between cracks and the larger-scale flaw structure.

Propagating cracks interact strongly with the sea ice microstructure, deviating into brine drainage structures when they are present and following the weak, defect-laden basal planes when passing through individual grains. Significantly, this was found to be true even for through-thickness cracks in floating first-year sea ice. Cracks in aligned sea ice strongly prefer to run perpendicular to the *c*-axis alignment direction. Observations in first-year sea ice reveal their preference to propagate along plate boundaries unless the background stress field is sufficient to drive the crack in some other direction.

Propagating cracks make minor adjustments in their paths as required to remain in the weak-fail direction as they pass from grain to grain, as seen in Fig. 13a, which shows the crack path in relationship to the microstructure. Crack paths in the weak-fail direction are relatively smooth macroscopically. On the other hand, cracks forced to run in the hard-fail direction (normal to the planes of weakness) propagate with greater difficulty and show evidence of a competition between microstructural influences and the global stress field. As a consequence, the crack follows a jagged, irregular path, as indicated by the photograph in Fig. 13b. This behavior is indicative of the crack's tendency to deviate onto weaker planes

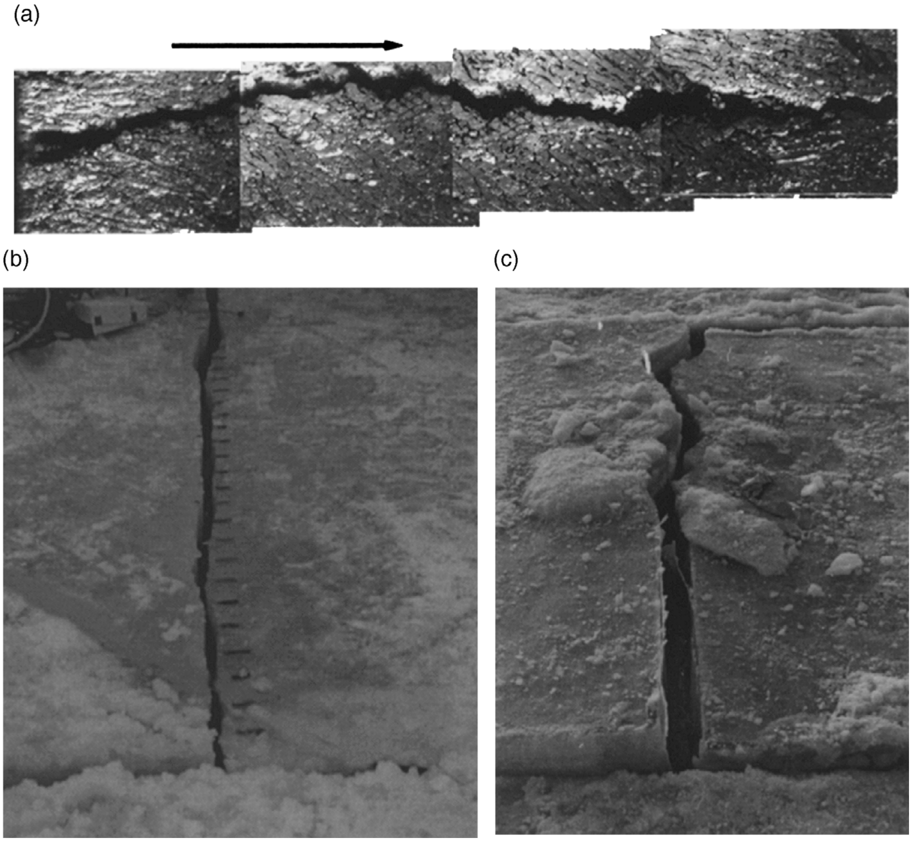

Fig. 13. Illustration of the influence of sea ice microstructure on the path of a through-thickness crack in first-year ice. (a) Mosaic of micrographs illustrating the crack's tendency to follow the weaker plate boundaries (indicated by the small-scale dark features). The arrow indicates the direction of propagation. (See Ref. [17] for a description of the related fracture experiments.) (b) Surface of an in situ specimen oriented in the easy-fail direction. Note the relatively smooth crack path for this orientation. (c) Surface of an in situ specimen oriented in the hard-fail direction. Note the jagged crack path.

wherever possible. The images in Fig. 13 were obtained during a set of experiments on young, 0.3-m-thick first-year ice in the Alaskan Arctic.

On the scale of meters, larger defects such as the brine drainage features discussed above begin to have an influence on crack behavior. Scale effect studies [67] indicate a shift in the observed size effect in the range of 1–3 m, and crack interaction with brine drainage structures appears to be associated with this transition. Visual examination of through-thickness crack surfaces in first-year sea ice clearly indicates that despite a macroscopically straight path, cracks continually undergo local deviations into brine drainage structures. Acoustic data obtained during crack propagation in floating sea ice indicate that through-thickness cracks run discontinuously, and that the jump distance corresponds reasonably well with the brine drainage network spacing (0.1–0.15 m).

Dempsey et al. [20] conducted large-scale fracture experiments on S1 freshwater ice that was very close to the melting point. Recall that this material has very large grains with the *c*-axes oriented predominantly in the vertical direction. The horizontal loading of the S1 microstructure results in very little resolved shear stress on the basal planes, so the constitutive behavior of this material could deviate significantly from that of the more common *c*-axis horizontal (S2) ice. Interestingly, the observed scale effects on the fracture of this ice do not respond to analytical treatments that have proven successful for smaller-grained, sea-ice specimens with horizontal *c*-axes. The behavior was attributed essentially to microstructural considerations: size effects on the tensile strength and fracture toughness were influenced by non-local (to the crack process zone) polycrystalline inhomogeneities.

7. Microstructural changes during deformation

The development of physically based models of the mechanical behavior of ice requires not only knowledge of the initial state of the material, but also knowledge of how properties change during deformation (strain history effects). Brittle tensile failure is ignored in the following since the first significant microstructural change (nucleation of a crack) is usually the last.

The key areas of concern are (1) changes in the dislocation density, which in turn influence the anelastic and viscous components of strain; (2) cracking, which reduces the elastic compliance, weakens the ice and sets the stage for subsequent failure processes; and (3) deformation-induced recrystallization, which causes changes in grain size, fabric and texture, and thus has a wide-ranging influence over subsequent flow and fracture characteristics. Although recrystallization is a very important area in ice mechanics, only the first two of these topics now receive further attention.

7.1. Dislocation density

It has been recognized for some time that dislocations play a significant role in ice deformation, and that the calculated total length of dislocations per unit volume (dislocation density) typically increases with strain. It has also been recognized that loading conditions of practical interest produce sufficiently high numbers of dislocations that it is difficult to determine the dislocation density directly with X-ray topography given the thickness required for structural stability of the specimen. This circumstance has stimulated the development of an indirect method to quantify the effective dislocation density through an analysis of the cyclic loading response of the material [26,58]. By using a dislocation-based model of the anelastic response under reversed direct-stress (cyclic uniaxial tension/compression) loading, it is possible to track changes in the effective dislocation density as a function of loading history.

Fig. 14a illustrates the significant change in the cyclic loading response that occurs as a result of creep deformation. The hysteresis loops were obtained under sinusoidal loading at the indicated creep strain levels. Fig. 14b shows the calculated dislocation density vs. strain as calculated from the hysteresis loop areas in Fig. 14a. Such experiments are leading to the development of an expression for the dislocation density as a function of stress, strain and temperature, and indicate that the viscous strain rate increases with the dislocation density during primary creep. Note that the influence of dislocation density on the viscous strain rate is distinct from the influence of other mechanisms (e.g. cracking or recrystallization). Cole and Durell [26] present detailed information on the manner in which dislocation density changes during creep deformation.

7.2. Cracking

Ice develops internal cracks under conditions that are relevant to many applications. Particularly in the important case of compressive failure in the ductile–brittle transition zone, cracking is intimately involved in establishing the peak loads experienced during the failure process. Researchers have examined internal cracking processes for many years, with the continuing work of Gold [46–48] providing a great deal of our current understanding of the relationship between microstructure and microcracking processes. Sinha [68,69] examined and modeled the crack population as a function of strain and loading conditions in

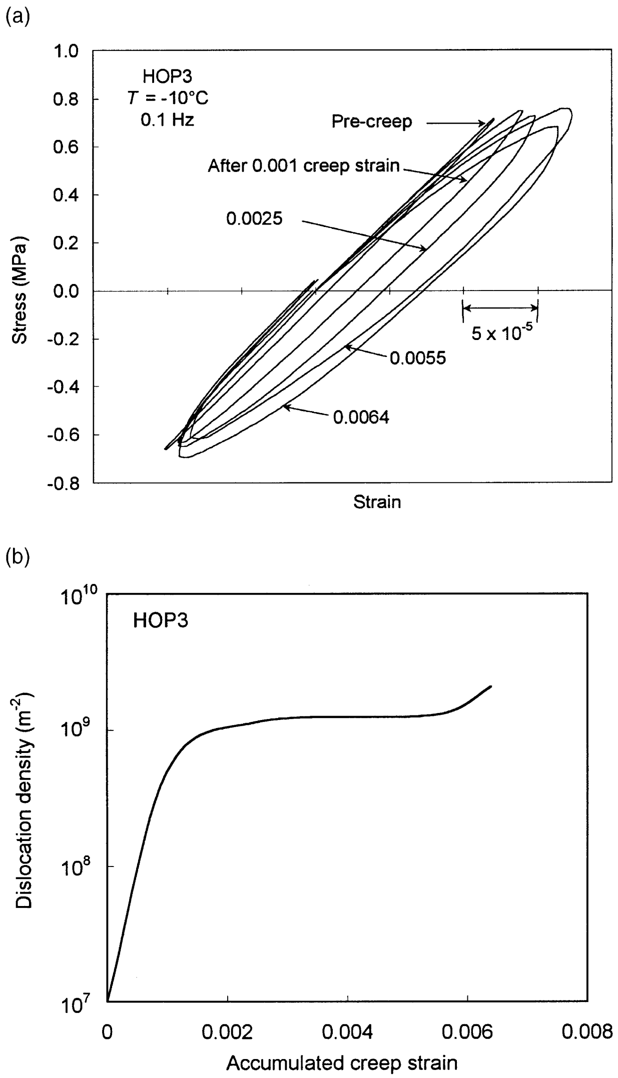

Fig. 14. Illustration of the significant change in the cyclic loading response of laboratory-prepared sea ice resulting from creep deformation under a stress of 0.5 MPa. (a) Hysteresis loops obtained under sinusoidal loading at the indicated accumulated viscous strain levels. (b) Calculated dislocation density vs. strain for the data in (a), using the model of Cole [57].

columnar-grained ice, and Cole [42] studied the relationship between grain size and crack size distributions in laboratory-prepared granular ice. Most work in this area has focused on characterizing nucleated, non-propagating microcracks that are visible to the unaided eye. While closely scrutinizing specimens in the very early stages of straining, Picu and Gupta [70] observed the formation of grain boundary decohesions that form prior to facet-sized microcracks in columnar freshwater ice.

The fact that ice fracturing is acoustically and electromagnetically active has allowed researchers to employ various monitoring techniques to help quantify fracturing processes. For example, Zaretsky et al. [71], Sinha [72], St. Lawrence and Cole [73] and Epifanov and Faustov [74] have used acoustic emissions (AE) monitoring techniques to help quantify the evolution of the crack population during laboratory experiments. Cole [42] coupled AE monitoring with direct observations to link AE amplitude distributions with crack size distributions. Using the fact that ice emits electromagnetic signals when it fractures, Petrenko and Gluschenkov [75] monitored EME from the in situ sea ice fracture experiments described in Ref. [17], to obtain information on crack velocity.

8. Concluding remarks

Since ice mechanics research in the last few decades has been largely driven by applications, the ultimate goal of the work is to produce quantitative models of mechanical behavior for predictive purposes. It is clear that the great range of size, thermal and loading conditions of interest in ice mechanics problems demands a set of specialized models, rather than a single, universal model. In general, models are required to describe constitutive behavior under arbitrary stress states in pure flow and flow with cracking as well as brittle compressive and tensile failure. The needs of specific applications dictate the thermal and loading regime, as well as the total strain levels, ice type and microstructural characteristics that are examined in the supporting experimental programs. As a consequence, there are some inherent limitations to the breadth of the experimental data available on any particular microstructural type of ice. For example, experiments on sea ice and columnar freshwater ice generally focus on relatively short-term engineering behavior, with an emphasis on establishing fracture strength and peak stresses during catastrophic failure processes. On the other hand, the bulk of granular ice studies, rooted as they are in glaciology, have focused primarily on long-term creep behavior with an emphasis on the effects of fabric development, stress state, and temperature on flow rates. Since many researchers have considered statistically isotropic granular freshwater ice to be well suited for studying fundamental aspects of ice deformation, that microstructure has perhaps been examined under the widest range of experimental conditions. However, because of the influence of microstructure on constitutive behavior, such a database is of limited use in the development of constitutive models for ice types having a significantly different microstructure. As a consequence, studies of materials such as atmospheric ice that do not closely conform to well studied ice types, will generally require at least some benchmark experiments to support a credible modeling effort.

Our understanding of microstructural influences on the strength and deformation of ice continues to improve, and the most important effects are generally being addressed in constitutive models and failure criteria. Because of the difficulty in developing fully mechanistic models of complex failure processes, generalized continuum models have frequently been employed, with an effort to empirically associate terms of the model with microstructural characteristics or relate them in some way to microphysical processes. Although such efforts have the advantage of applying an analytically rigorous framework to the problem, the lack of a clear connection between the model and the underlying physical processes limits their reliability upon extrapolation. Despite their potential complexity, mechanistic models offer more confidence upon extrapolation, and much of the recent work discussed above supports the development of mechanistic constitutive and fracture models of ice. Given the range of scale and complexity of the scientific and engineering problems that will employ such models, the required level of sophistication of the models is expected to be quite variable. However, the foregoing discussions make it abundantly clear that substantial progress in our ability to model the macroscopic mechanical behavior of ice with confidence hinges on a thorough understanding of its behavior at the microstructural level.

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