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## ANNEALING RECRYSTALLIZATION IN LABORATORY AND NATURALLY DEFORMED ICE

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Résumé - Des résultats concernant la recristallisation après recuit sont présentés ; ils concernent la glace naturelle et la glace artificielle déformée. Des lames minces ont été réalisées pour suivre la recristallisation qui, dans le cas de pastilles de glace fortement compressées et recuites à  $-3^{\circ}\text{C}$  montre que dès qu'un nouveau cristal est créé dans la matrice de glace déformée il conserve son orientation pendant toute la durée de la recristallisation. Des recuits à pression normale d'échantillons fortement déformés et texturés de glace profonde des glaciers d'Antarctique ont conduit à faire grossir de très gros cristaux possédant des orientations d'axe c très modifiées par rapport à la glace initiale. Les textures de la même glace recuite sous 200 bars de pression hydrostatique ressemblent à celles observées dans la glace lors de la recristallisation dynamique à 190-200 bars qui est la pression existant près de la base du manteau de glace. Cette pression est aussi celle qui, à cet endroit, correspond en Antarctique à la fusion.

ABSTRACT. Results are presented of annealing recrystallization in both naturally and laboratory deformed ice. Thin section techniques were used to follow the progress of recrystallization which, in the case of highly compressed ice pellets annealed at  $-3^{\circ}\text{C}$ , showed that as soon as any new crystal was nucleated in the deformed ice matrix its retained its lattice orientation over the duration of the recrystallization. Laboratory annealing at ambient pressures of highly deformed, strongly oriented crystal ice from cores deep in the Antarctic Ice Sheet resulted in growth of very large crystals exhibiting c-axis orientations very much degraded with respect to the original ice. Textures and fabrics of the same ice annealed at 200 bars confining pressure closely resembled those observed in ice undergoing dynamic (annealing) recrystallization at 190 - 200 bars overburden pressure near the base of the ice sheet, which at this location in Antarctica was at pressure melting.

## INTRODUCTION

Primary recrystallization, including annealing recrystallization, involves nucleation and growth of strain-free grains at the expense of plastically deformed grains of the same material. Excess energy stored in the deformed grains provides the driving force for this kind of recrystallization, which if it occurs during deformation (such as in actively deforming glacial ice), is termed syntectonic or dynamic recrystallization. If recrystallization occurs following deformation it is called annealing recrystallization.

Despite the importance of understanding the nature of such recrystallization in glacial ice, and its effect on the rheological and mechanical properties of ice, rather few attempts have been made to foster this understanding through testing under controlled conditions in the laboratory. Apart from the earlier work of Steinemann [1], Rigsby [2], Wakahama [3] and Gow (in Abele and Gow [4]) the most recent investigations appear to be those of Wilson [5] involving studies of changes in the microstructure (c-axis orientation) and texture of polycrystalline ice compressed at temperatures of  $-10$  and  $-1^{\circ}\text{C}$  and annealed at  $-1^{\circ}\text{C}$  without load.

Extending this work further, we here describe the results of thin section analyses of annealing recrystallization in both experimentally and naturally deformed ice.

#### EXPERIMENTAL RESULTS AND DISCUSSION

The initial series of tests was performed on fine-grained ice produced by crushing and compressing fragments of single crystal ice in a pelletizer (Figure 1). Ice fragments were compressed incrementally to a nominal pressure of 200-235 bars at  $-8^{\circ}\text{C}$  in a 4mm diameter cylinder equipped with a vacuum device for removing air from the sample. The final pressure was maintained for about two hours before depressurizing. Pressure in the cylinder was then released slowly enough to prevent cracking of the pellet of compressed ice. The pellets, measuring up to 32mm thick

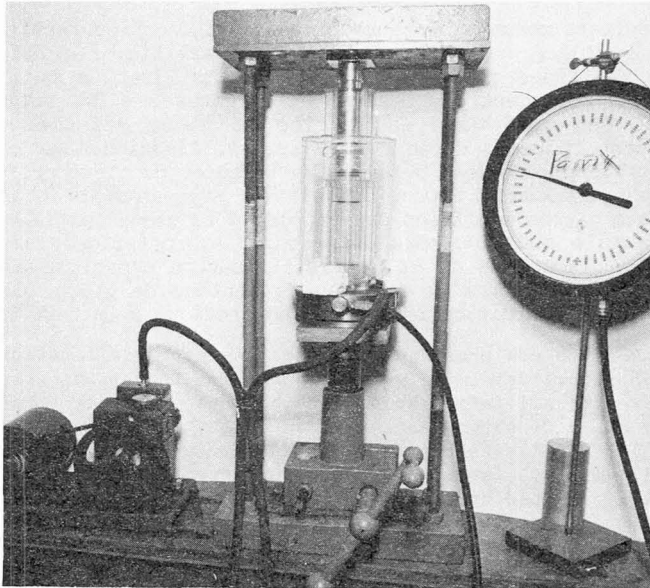


Fig. 1. Apparatus for fabricating highly compressed ice pellets for annealing experiments.

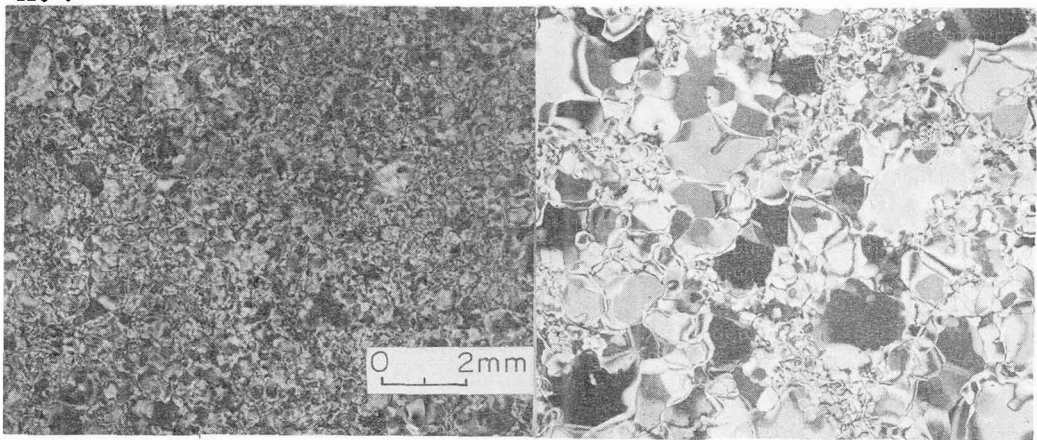
and essentially bubble free, were removed and sectioned quickly on a microtome. Sections measuring 1mm thick were then transferred to a constant temperature box, maintained at  $-3^{\circ} \pm 0.1^{\circ}\text{C}$ , and photographed at intervals during the recrystallization process. Photographic documentation included both movie and still camera techniques.

A typical sequence of time lapse photographs, taken between crossed polaroids with a 100 X 125mm bellows extension camera at seven times natural scale, is shown in Figure 2.

Photograph A illustrates the structure of the ice pellet approximately 15 minutes after it was removed from the pelletizer. Photograph D shows the extent of recrystallization five days later. Photos B and C taken at intermediate stages demonstrate how an aggregate of deformed fine-grained crystallites recrystallizes into a coarse-grained mosaic of substantially strain-free, randomly oriented crystals. The driving force for this recrystallization is the excess energy stored in the ice during compressive deformation in the pelletizer. Significant aspects of this recrystallization include the following observations. 1) As soon as a new grain is nucleated it retains the same c-axis orientation throughout the entire process of recrystallization. 2) 50% of the recrystallization was accomplished in about one hour. 3) The new generation of crystals continues to grow until mutual impingement with neighboring grains inhibits further coarsening. 4) Recrystallization continues until all the original fine-grained matrix is entirely

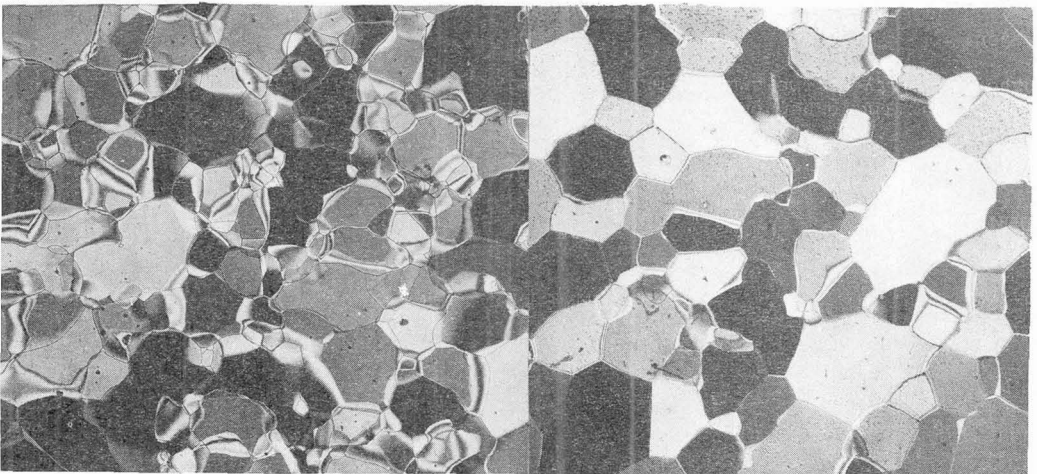
consumed by the growth of new crystals. Final recrystallization is concerned primarily with elimination of residual pockets of strain as the transformation from C to D in Figure 2 clearly demonstrates. This stability of structure, directly related to the formation of strain-free crystals, is also accompanied by straightening out of grain boundaries and by the widespread occurrence of equigranular ( $120^\circ$ ) grain boundary intersections. This recrystallization was not accompanied by any significant orienting of crystal c-axes into a preferred fabric. Experiments with several other pellets indicated that the locations of nucleation sites within the deformed matrix probably coincide with either the positioning of impurities in the ice and/or with regions of greatest damage incurred during confined compression.

The recrystallization path, illustrated in Figure 2, compares closely with the changes in microstructure and texture that Wilson [5] observed in polycrystalline ice compressed at  $-10^\circ\text{C}$  and then annealed at  $-1^\circ\text{C}$ . Wilson [5] noted the same marked grain size variations occurring at the outset of annealing which become much less once the curvature of the grain boundaries had decreased and the shapes of the grains had become polygonal and commonly intersected at angles of  $120^\circ$ .



A: 0.25 hr

B: 1.2 hr



C: 20 hr

D: 120 hr

Fig. 2. Time lapse photography of annealing recrystallization in a 1mm thick section of ice formed from ice fragments crushed and compressed to 235 bars at  $-8^\circ\text{C}$  and subsequently annealed at  $-3^\circ\text{C}$  for 120 hours.

In a second series of tests, 5cm long core samples from representative levels in the 2164m long ice core from Byrd Station, Antarctica were hydrostatically compressed to 200 bars for one month in a pressure chamber filled with kerosene and maintained at a temperature closely approximating the pressure melting point ( $-1.7^{\circ}$  at 200 bars). Resultant textures and c-axis fabrics obtained from thin sections of each bulk sample (composed of at least 500 crystals at the outset of testing) were then compared with original glacial textures and fabrics, measured prior to annealing [6], and with the textures and fabrics of thin sections of a second set of specimens from the same suite of samples recrystallized at ambient pressures and  $0^{\circ}\text{C}$  in kerosene-filled containers in a water bath.

Results obtained with relatively unstrained ice from 100m and with highly deformed ice from 1800m in depth are presented in Figure 3. In both samples the mean diameter of crystals measured 4-5mm, but in other respects the englacial characteristics of the two samples differed drastically. Whereas original ice from 100m contained abundant air bubbles and consisted of crystals with randomly

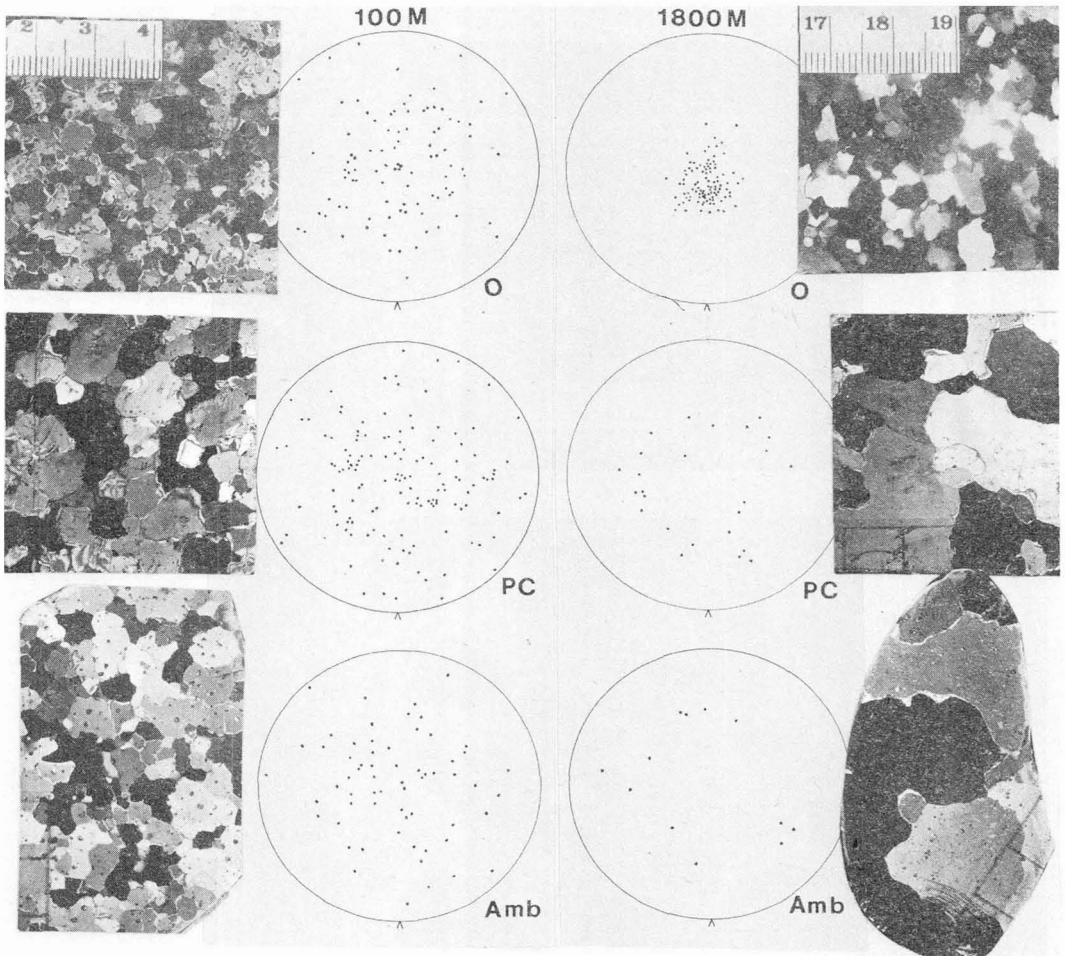


Fig. 3 Textures and c-axis fabrics of two Antarctic Ice Sheet core samples from 100m and 1800m depth respectively before (0) and after annealing at the pressure melting point for one month at 200 bars in a pressure chamber (PC) and at ambient pressure (Amb). Smallest scale subdivisions on photos measure 1mm. Scale is same for all micrographs.

distributed c-axes, the 1800m sample originally contained air dissolved in the ice [7, 8] and was composed of crystals that exhibited a very tight single-pole fabric consistent with substantial horizontal shearing at this depth in the ice sheet. Following testing, both the compressed and uncompressed samples of 100m ice were found to have undergone two-to-three fold increases in crystal size, but this growth resulted in no significant changes in c-axis orientation; the essentially random distribution of c-axes in the original ice was still retained in the recrystallized ice. This situation was in marked contrast to changes that occurred in both the test pieces from 1800m. These changes included a five-fold increase in crystal size in the unconfined sample and a three-fold increase in the hydrostatically compressed sample. In the latter case, recrystallization under high confining pressure appears to have constrained both crystal growth and the bubbling out of dissolved air which, in the unconfined sample, has led to the formation of numerous air bubbles. In addition, both test pieces underwent major changes in fabric in which the original tight clustering of c-axes degenerated into a ring-like, dispersed pattern of c-axes. This breakdown of fabric, occurring in conjunction with major changes in the texture of the ice, is in complete accord with observations made by Rigsby [2] on the annealing at 0°C of a section of Greenland ice exhibiting the same texture and fabric as the 1800m sample from Byrd Station. After annealing for one month, Rigsby [2] found that sixteen large crystals now existed in place of the more than 300 crystals present prior to annealing and that the spread of c-axes was greater than even the most divergent of crystal axes in the original single-pole fabric, similar to the situation found after annealing of the 1800m sample from Byrd Station. These observations clearly show that annealing textures are not controlled by the orientation characteristics of the original crystals, otherwise crystals with vertical to near-vertical c-axis orientation should have dominated as the ice recrystallized.

The laboratory annealed ice from 1800m closely simulates in all aspects of its recrystallized condition the structure observed in ice from the bottom 300m of the ice sheet at Byrd Station [6]. Such structure has been attributed [6] to dynamic (annealing) recrystallization of fine-grained, single-pole ice of the kind exemplified by the sample from 1800m. The 200 bar pressure chosen for the laboratory experiments closely approximates the overburden pressure at the bottom of the 2164m thick ice sheet at Byrd Station where the ice is known to be at the pressure melting point [9].

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## COMMENTS

E. GAFFNEY :

- Regarding the paper on annealing (p. 127-130), do you have any evidence on the shape stability of the crushed material during the annealing process ?

Answer:

- The thin section itself underwent no shape change. The pellet from which the section was made underwent slight internal cracking some time after the pellet was removed from the pelletizer, but there was no visible change in its shape.

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E. GAFFNEY :

Regarding the paper on thin sections (p. 135), it appears that you have, not only straightening of the boundaries and increase in the grain size, but also notation of the grain boundaries to become perpendicular to the plane of the section. One should be able to determine the vertical profile of these boundaries by contouring the birefringence change across the grain boundary.

Answer:

This is a good point and I agree. The sharp-lined nature of many boundaries in the recrystallized section after 120 hours of annealing certainly implies that these boundaries are indeed vertical to the plane of the section, that is they exhibit little or no curvature in the vertical.

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J.W. GLEN

In my old work on creep of ice Glen (1952), and in Steinemann's work at the same time, the recrystallization after straining was studied in this way. In my work I followed primary recrystallization after the stress was removed in a thin section, but also at the same time took repeated sections from the bulk to see to what extent the recrystallization in thin section mirrored that in the bulk. Not surprisingly the bulk recrystallization proceeded faster. Did you do tests of this kind ?

Answer :

We also did some periodic sectioning of bulk samples (pellets) and observed recrystallization textures were similar to these observed at different stages of recrystallisation of the thin sections described in the paper.

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J.W. GLEN

Surely once the grains have grown, even your thicker specimens will be thinner than the grain size and so section thickness will then inhibit further growth.

Answer :

This is what my data also shows and I agree entirely with your comment.