Preferred crystal orientation in quietly frozen freshwater bodies

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Introduction

In natural freshwater ice covers, the crystal c-axes are sometimes observed to lie predominantly in the horizontal plane and sometimes in the vertical. It is believed that either the conditions in the water column (Shumskii, 1964), or the crystallography of the initial ice skim determine the dominant crystal-orientation (Gow, 1986). The process which selects the preferred orientation is called *geometric selection* and studies by Kolmogorov (1949) and Gray (1984) on two-dimensional systems show that the decrease in crystal number during geometric selection is inversely proportional to the initial crystal density.

It is a well documented fact that ice grows faster in the direction perpendicular to the c-axis than in the parallel direction (e.g. Weeks and Wettlaufer, 1996).

The purpose of this study is to understand the c-axis orientations in freshwater in order to explain and predict crystal structures in quietly frozen lakes. We present results of experiments on quietly frozen ice sheets of fresh water, frozen under different thermal conditions and from different initial ice skims.

Two Hypotheses

A. The crystallography of the initial ice skim fully specifies the favored crystal orientation

This explanation has been favored by Gow (1986) based on his observations from several New England lakes and from experiments. He found that in the absence of seeding, c-axis vertical orientations were dominant. Ice grown from seeded initial ice skims showed c-axis horizontal orientations to be dominant. No explanation is given on how the initial ice skim affects the process of geometric selection.

B. The thermal characteristics of the underlying water body control the favored crystal orientation

This hypothesis has been brought forward by Shumskii (1964) and is briefly summarized by Weeks and Wettlaufer (1996). It suggests that if, after initial ice formation, there is a positive downward temperature gradient in the layer below the ice-water interface, and if the interface lies at the 0ºC isotherm, then c-axis vertical crystals have a lateral growth advantage. This is due to the fact that c-axis horizontal crystals would protrude into water above the freezing point, i.e. their easy growth direction is exposed to a layer of water in which they cannot grow. However, if the layer of water below the ice water interface is at 0ºC, or even supercooled, c-axis horizontal crystals have a growth advantage and will eventually wedge out other crystals. This theory is supported by the experimental data of Cherepanov and Kamyshnikova (1973).

Experiments

The 1000 litre experimental tank can be heated from the bottom and the sides in order to control the temperature gradient in the water column and prevent ice formation on the bottom. The cold room can be set to any air temperature between 0 ºC and -20 ºC.

The temperature profile in the water and ice is monitored using an array of thermistors with vertical separations ranging from 1 cm to 10 cm. Seeding of ice sheets was accomplished using crushed ice made from filtered tap water or water sprayed into the cold air above the water body.

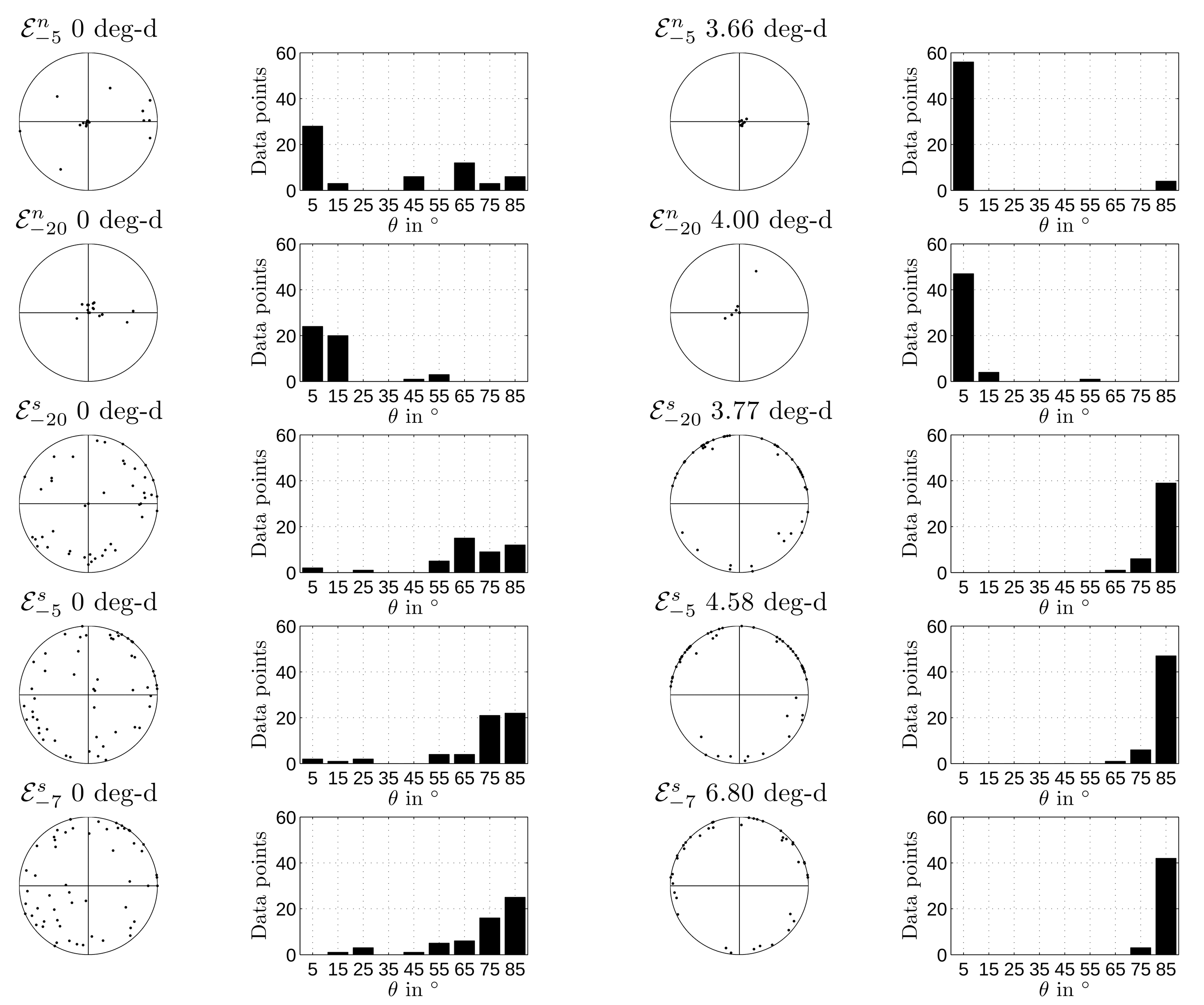

Figure 1: Schmidt net plots of c-axis orientations and histograms of inclination angle distribution for seeded and unseeded experiments. The plots on the left-hand side show data from the initial ice skim; the right-hand side shows data from later in the experiment. Notation: $\mathcal{E}$ stands for Experiment, superscripts n and s for unseeded and seeded and subscripts are the air temperature in ºC. The inclination angle is measured from the vertical and the timescale 'freezing degree-days' (deg-d) is defined as the product of time and ice surface temperature integrated over the time from the onset of freezing.

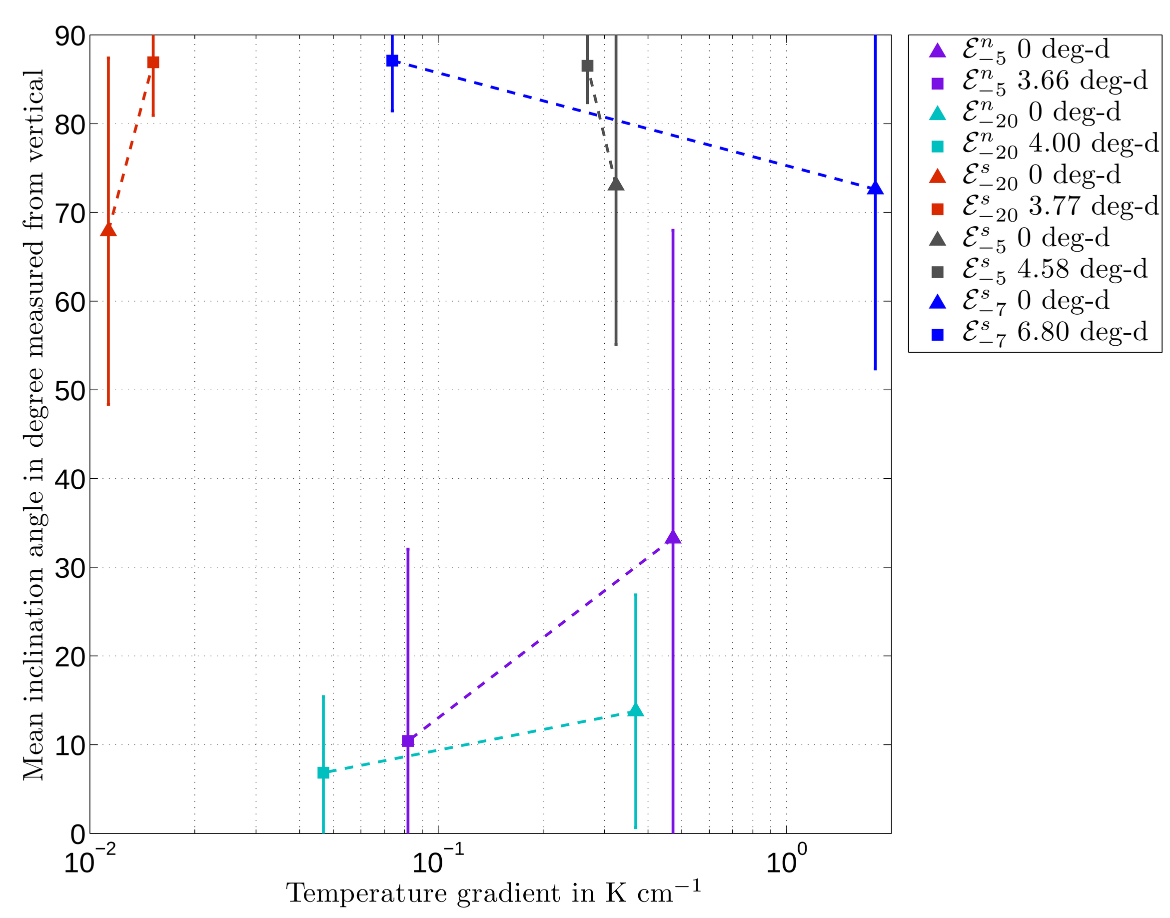

Figure 2: Plot of the mean inclination angle over the temperature gradient in the 4 cm of water column adjacent to the ice-water interface. Note the logarithmic scale for the temperature gradient.

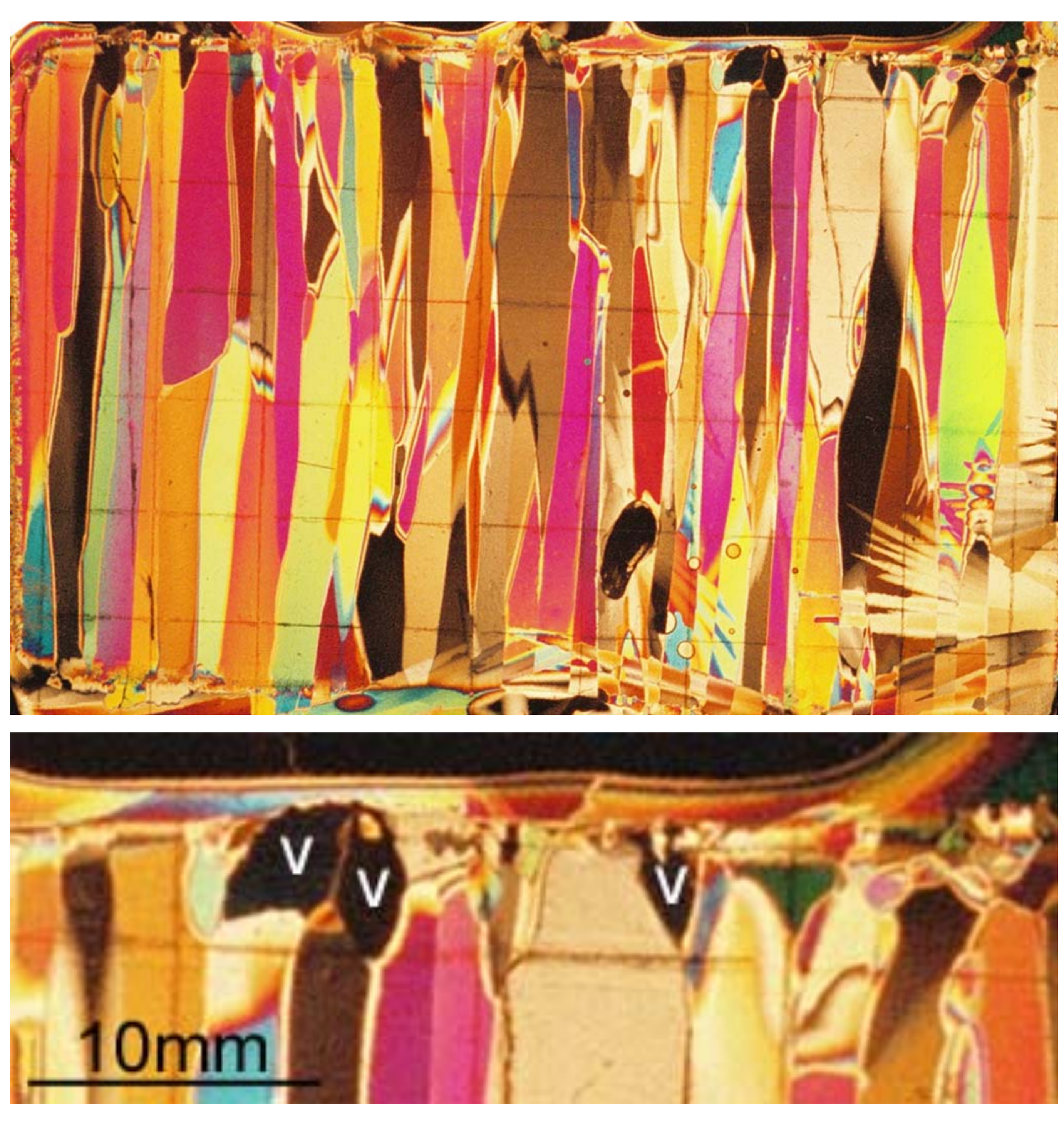

Figure 3: Top: Full vertical thin section of a crushed ice seeded ice sheet. Bottom: Enlargment of the upper right corner of the image above. Crystals marked with 'v' are c-axis vertical. It can be seen how fast they are being wedged out.

Results

Figure 1 shows that unseeded ice sheets develop c-axis vertical fabrics while seeded ice sheets form c-axis horizontal fabrics. The dominance of c-axis horizontal crystals appears to be independent of the temperature gradient in the water column (Figure 2).

During seeding it was observed that the initial ice skim did not freeze instantaneously, but that partial melting took place initially. This observation is supported by temperature records of the seeded experiments. Furthermore, the initial ice-water interface in the seeded experiments was rough: that is, it consisted of cavities and projections.

Discussion

Although the results seem to support hypothesis A there is evidence that they are better interpreted in an amended version of hypothesis B. As hypothesis B assumes a flat interface throughout freezing it does not account for the initial roughness of the ice-water interface during initial freeze-up.

Hypothesis B amended

Following assumptions by Tiller (1957) and Wilen and Dash (1995) regarding cavities in ice sheets, we assume that the water in the cavities in ice sheets in the seeded case is at the freezing point, or even slightly supercooled. At the same time, the projections in the interface protrude into water above the freezing point and melt. Hence, during seeding a layer of water at the freezing point develops adjacent to the ice-water interface. The lateral growth advantage of c-axis vertical crystals is removed by neighboring crystals. However, c-axis horizontal crystals have a vertical growth advantage: that is, they can grow rapidly into the layer of cold water. By the time the system relaxes to a flat interface all c-axis vertical crystals are wedged out since, due to the high crystal density, geometric selection happens very fast.

Outlook

More experiments are needed to confirm the amended hypothesis B. A higher resolution in the temperature records in the upper water layer and initial ice skim should be attempted. Three-dimensional models for geometric selection, following the approaches by Kolmogorov and Gray, are needed for a better understanding of the coupling of the decrease in crystal number and the initial crystal density.

References

Cherepanov, N.V. and A.V. Kamyshnikova, Sizes and shapes of congealed-ice crystals. Studies in Ice Physics and Ice Engineering, Ed. G.N. Yakovlev, Israel Program of Scientific Translations, pages 170-176.

Gow, A.J., Orientation Textures in Ice Sheets of Quietly Frozen Lakes, Journal of Crystal Growth 74 (1986) 247-258.

Gray, N.H., Geometric Selection in Two-Dimensional Crystal Aggregates, Mathematical Geology, 1984, 16, 91-100.

Kolmogorov, A., Geometric selection of crystals, Doklady Akademii Nauk SSSR, 1949, 65, 681-684.

Tiller, W., Preferred Growth Direction of Metals Journal of Metals, 1957, 847-855.

Shumskii, P.A., Principles of Structural Glaciology, trans. D. Krauss, (Dover Publications, 1964).

Weeks, W.F. and J.S. Wettlaufer. Crystal orientations in floating ice sheets. The Johannes Weertmann Symposium, pages 337-350, 1996.

Wilen, L. and J. Dash, Giant faces at ice grain boundary grooves Science, 1995, 270, 1184-1186.