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Crystal fabrics of basal ice near Hamna Icefall, East Antarctica

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Abstract

The present paper mainly discusses crystal fabrics of debris-laden basal ice near Hamna Icefall, Queen Maud Land, East Antarctica. The basal ice consists of alternating layers of bubble-free and bubbly ice of the order of millimeter to centimeter in thickness. Detailed analysis of crystal fabric of the alternating layers was performed. As a result, the crystal fabrics of the alternating layers have a multiple maximum pattern, and are homogeneous without dependence on the stratigraphy of bubbles. The multiple maximum pattern is suggested to be formed due to by recrystallization. The basal ice is considered to be suffered by recrystallization as a final physical process before the arrival at the Hamna Icefall.

1. Introduction

In order to make clear flow dynamics of ice sheets and glaciers, it is necessary to elucidate physical properties of the basal part of the ice sheets and glaciers. In general, the basal part of the ice sheets and glaciers consists of debris-laden basal ice. Because the debris-laden basal ice has specific physical properties as compare to ordinary ice sheet ice without debris, it is important to make clear physical properties of the basal ice. Analysis of crystal fabric of basal ice is one of the most promising techniques to elucidate physical properties of the basal ice.

The present paper reports crystal fabrics of basal ice near Hamna Icefall, Sôya Coast, East Antarctica, and discusses physical properties of the basal part in the Sôya drainage. Kizaki (1962) measured crystal fabrics of Hamna Icefall. He showed that the crystal fabric of the basal part in Hamna Icefall consists of a multiple maximum pattern, and suggested that the multiple maximum pattern is caused by long-time shearing during the flow to the marginal part of the Sôya drainage. Iizuka *et al.* (2001a and 2001b) discussed formation processes of the basal ice near Hamna Icefall (hereafter: the Hamna basal ice), using stratigraphic features, co-isotopes and chloride ion of the Hamna basal ice. A summary of the studies is given below.

1) The Hamna basal ice about 6.8 m thick exhibits two peculiar stratigraphic features. One is the upper part of the basal ice (5.5 m in thickness), which consists of alternating layers of bubble-free and bubbly ice on the order of millimeter to centimeter in thickness. The other is the lower part of the basal ice (1.3 m in thickness), which consists predominantly of bubble-free ice.
2) The Hamna basal ice and ice sheet ice above the basal ice originated from precipitation in the inland regions of the Sôya drainage of the ice sheet.
3) It has been suggested that the bubble-free ice layers and the bubbly ice layers whose isotopic fluctuation is decreased from that in neighboring bubble-free ice, were formed by a regelation process in an open system (Souchez and Jouzel, 1984; Souchez and de Groote, 1985), and the bubbly ice layers having quasi-neutral values on the isotopic profile were not affected by melt-refreezing.
4) It has been suggested that the alternating layers of bubble-free and bubbly ice layers have been formed by piling up of freezing layers and non-melted layers followed by folding.

Based on the summary, fabric analysis with a measuring interval of the order of millimeter is needed to elucidate the physical properties of the Hamna basal ice, because the Hamna basal ice consists of the alternating layers on the order of millimeter to centimeter in thickness formed by different processes.

2. Study site and analytical procedures

A basal ice sampling site was selected at the left bank near Hamna Icefall located at 30 km south of Syowa Station, Sôya Coast, Queen Maud Land (69°20′ S, 39°45′ E). Further details of the study site are reported by Iizuka *et al.* (2001a).

Analysis of crystal fabric was performed in the cold rooms (−20°C) at the Institute of Low Temperature Science and National Institute of Polar Research. Two kinds of laboratory analyses, which have different measurement intervals, were conducted. The first was a general analysis of the entire basal ice layer and ice sheet ice above the Hamna basal ice. Analysis for crystal fabric was performed every 500 mm in thickness. The second was a detailed analysis focusing on particular stratigraphic sections. A characteristic part about 40 mm in length was used for detailed analysis of crystal fabric, which was done every 5 mm in thickness. For the ice sheet ice above the Hamna basal ice, the crystal fabric was measured in thin sections of ice with perpendicular to the height (thickness) direction. For the Hamna basal ice, the crystal fabric was measured in thin sections of ice with parallel to the alternative layers (inclined about 5 to 15 degrees to the horizontal direction). The Rigsby stage and the Schmidt plot were used to measuring and plotting the c-axis orientations.

3. Results

Figure 1 shows vertical profiles of crystal size of the Hamna basal ice. Almost crystal sizes are within 7 ~ 20 millimeter. These sizes are larger than those observed in Antarctic ice cores; for example, these sizes of the Hamna basal ice correspond to those below 2400 m in depth of Dome F (Azuma *et al*., 2000).

Figure 2 shows Schmidt plots of the crystal fabrics of the Hamna basal ice and the ice sheet ice above the Hamna basal ice. The crystal fabrics of the upper and lower parts of the Hamna basal ice have a similar pattern of a multiple maximum fabric whose center is plotted at the center on the Schmidt plot. The crystal fabrics of the ice sheet ice show also a multiple maximum fabric. The center of the multiple maximum pattern, however, slants at the center on the Schmidt plot.

Figure 3 shows Schmidt plots of the crystal fabrics of the particular alternative layers. Both of the

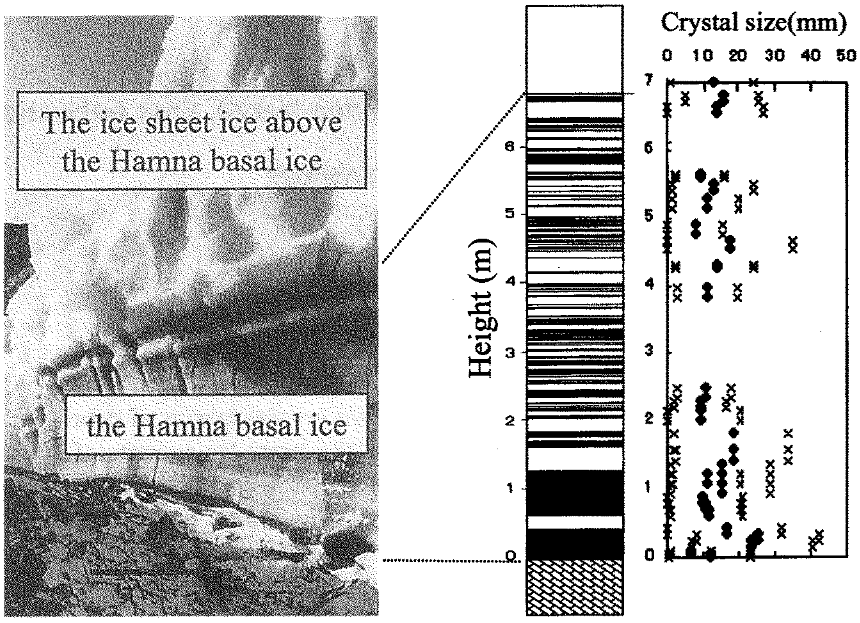

Fig. 1. Picture of sampling site, stratigraphy and crystal size of the Hamna Basal Ice. This ice cliff is about 30 m high and debris-laden ice (= basal ice) is about 6.8 m in thickness. The basal ice and the upper ice sheet ice of the cliff were sampled through 8 m in thickness. Bubbly ice layer is represented by open spaces and bubble-free ice layer by black spaces in the column. The black circles and crosses in the profile of crystal size are represented the average values and the standard deviations of polycrystalline ice about 100 millimeter thick in Hamna basal ice.

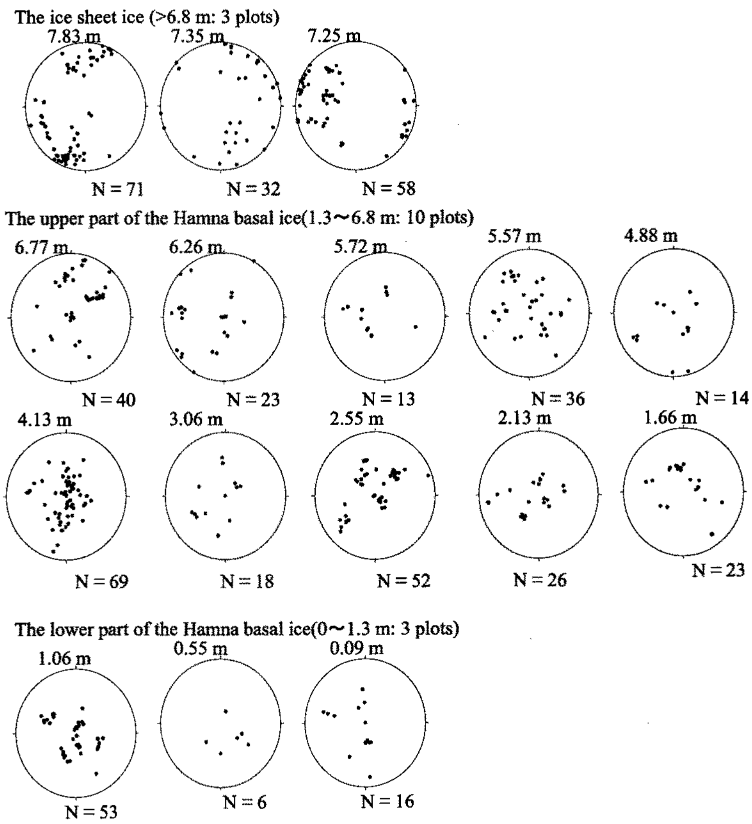

Fig. 2. Crystal fabrics of the Hamna Basal Ice. Schmidt plots of the c-axis orientations of the upper part of basal ice, the lower part of basal ice and the ice sheet ice above the basal ice are shown at 10, 3 and 3 plots, respectively. N written under each plots indicates the measured numbers of ice crystals in a thin section. The Schmidt plots are represented that the center of the plot shows vertical direction compared to the thin section.

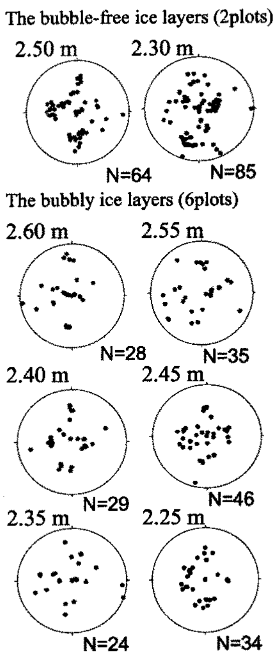

Fig. 3. Crystal fabrics of the particular alternative layers in the upper part of the Hamna Basal Ice. Schmidt plots of the c-axis orientations of the bubble-free and bubbly ice layers are shown at 2 and 6 plots, respectively. N written under each plots indicates the measured numbers of ice crystal in a thin section.

bubble-free and bubbly ice layers in the alternative layers have a pattern of multiple maximum fabric, and can not be observed the difference of fabric pattern between the two. This result indicates that the fabrics of the Hamna basal ice are homogeneous without dependence on the stratigraphy of bubbles.

4. Discussions

Azuma (1994) theoretically showed the fabric development by simulation based on lattice rotation and predicted the fabric development of the ice sheet. He suggested that the crystal fabric of the basal part of the ice sheet shows an single maximum pattern whose center is plotted at the center on the Schmidt plot due to suffering of simple shear, if the thin section of ice is measured for parallel to the shear plane. The Hamna basal ice is considered to be also suffered by simple shear and has been shown the single maximum pattern, because simple shear is a typical mechanism of the basal and marginal part of the ice sheet (e.g. Fujita *et al.*, 1999). The crystal fabrics of the Hamna basal ice, however, show the multiple maximum pattern. The multiple maximum pattern indicates that the Hamna basal ice has been suffered by not only simple shear but also other physical processes.

Watanabe and Ôura (1968) showed experimentally that an ice fabric of four (multiple) maximum pattern is formed by suffering of uniaxial compression. Matsuda and Wakahama (1978) observed ice fabric of four (multiple) maximum pattern at the bottom parts of the ice cores in Antarctica, and suggested that a great majority of the adjoining crystals may be in a twinning relation. Jacka and Li Jun (2000) suggested from experiments of uniaxial compression that small circle pattern, which is very similar to the multiple maximum pattern, is formed by recrystallization at higher temperature and stress from a single maximum pattern. A basal part of the Sôya drainage is considered to be a circumstance of relatively higher temperature close to melting point of ice, because some of ice layers in the Hamna basal ice were formed by regelation process (Iizuka *et al.*, 2001a). The fabrics of the Hamna basal ice are homogeneous, besides both of the bubble-free and bubbly ice layers in the alternative layers have a pattern of multiple maximum fabrics (Figs. 2 and 3). This homogeneous is suggested that a physical process, which formed the multiple maximum pattern, had affected the entire of the Hamna basal ice after formation of the alternative layers. Recrystallization is one of the plausible physical process to affect crystal fabric after formation of the alternative layers. Matsuda and Wakahama (1978) showed that c-axis orientations in a polycrystalline glacier ice followed by recrystallization have singular angles of 22.5° and 67.5° compared to the center of fabric, if the fabric is measured parallel to shear plane. Fig. 4 shows angles of c-axis orientations in the Hamna basal ice compared to the direction of the alternative layers which are considered to parallel to shear plane. Most angles of c-axis orientations in the Hamna basal ice agree with that given by Fig. 4 in Matsuda and Wakahama (1978). From these considerations, a recrystallization process is probably suited for the formation of the crystal fabric observed in the Hamna basal ice. The large crystal sizes consisting of 7 ~ 20 millimeter support the consideration that a recrystallization has worked to the Hamna basal ice.

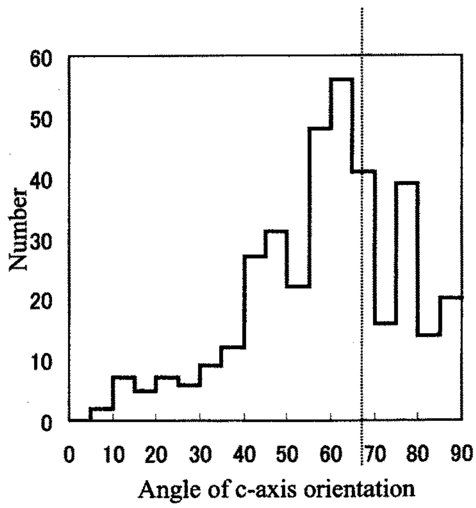

Fig. 4. Histogram of the angle between the c-axis orientation and the alternative layers of the Hamna basal ice. The dotted line indicates the preferred angle shown in Matsuda and Wakahama (1978).

The ice sheet ice is considered to be also suffered by recrystallization, because the ice sheet ice consist of a multiple maximum fabric (the upper 3 polts in Fig. 2). The slanting of the center of multiple maximum pattern observed in the ice sheet ice is probably caused by difference of directions between measured plane of thin sections and shear plane.

Figure 5 shows schematic diagrams of expected histories of the ice fabric in the basal part of the Sôya drainage. The fabrics of the Hamna basal ice and the ice sheet ice are considered to have shown the single maximum pattern due to simple shear at the lower part of the ice sheet (① in Fig. 5). Hudleston (1976) suggested that a fabric of ice suffered by folding becomes two maxima pattern. The fabric of the alternating layers might have shown the two maxima pattern (② in Fig. 5). Jacka and Li Jun (2000) suggested that the small circle pattern formed by recrystallization process is independent of preliminary fabric pattern of ice before the recrystallization. The Hamna basal ice which preliminarily had shown single or two maximum fabrics, is considered to be suffered by recrystallization as a final physical process before the arrival at the Hamna Icefall (③ in Fig. 5).

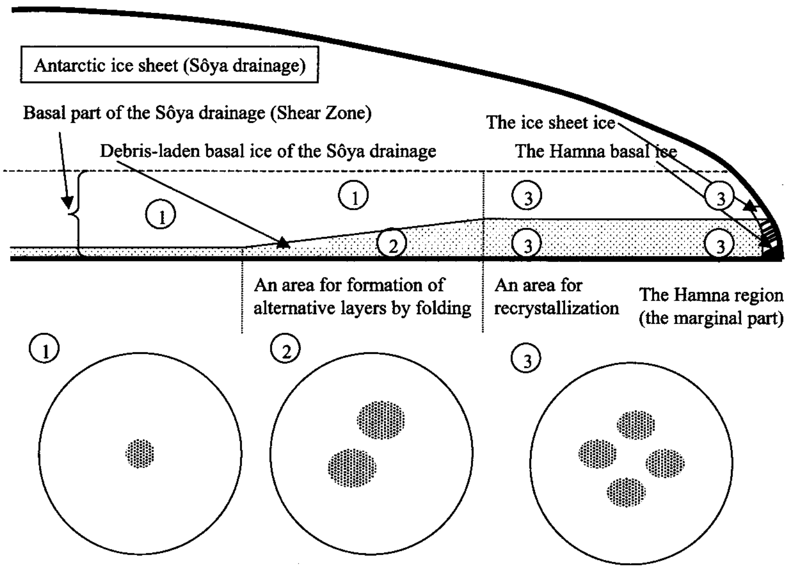

Fig. 5. Schematic diagrams of expected fabrics in the basal part of the Sôya drainage. ①: An area where the basal part of the Sôya drainage suffered by simple shear; ②: An area where the alternative layers were formed by folding; ③: An area where the sheared and/or folded layers were suffered by recrystallization. Three plots are considerable fabrics in each area. The dotted ranges in the each plots indicate the concentrated area of the c-axis orientations.

5. Conclusion

We have discussed crystal fabrics in the Hamna basal ice. The crystal fabrics of the Hamna basal ice have a multiple maximum pattern whose center is plotted at the center on the Schmidt plot, and are homogeneous without dependence on the stratigraphy of bubbles. The multiple maximum pattern is suggested to be formed by recrystallization process. It is considered that the Hamna basal ice is suffered by recrystallization as a final physical process before arrival at the Hamna Icefall.

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