

## Formation processes of a pocket consisting of bubble-free ice in Hamna ice cliff, Sôya Coast, East Antarctica

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**Abstract:** To clarify the basal hydrology of Sôya drainage, East Antarctica, we studied the formation processes of a pocket consisting of bubble-free ice in Hamna ice cliff, Sôya Coast by using stable isotope ratios ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ). The stable isotopes of this bubble-free ice are almost the same values without  $\delta$ -value fluctuations as those from Rayleigh-type fractionation; isotopically, the bubble-free ice was heavier by 3.8 and 27‰ for  $\delta^{18}\text{O}$  and  $\delta\text{D}$ , respectively, than the neighboring bubbly ice. These results suggest that the pocket was formed by meltwater refreezing during the discharge of water to the lower reach under the Sôya drainage. Meltwater under the Sôya drainage is considered to have flowed through R-channels.

### 1. Introduction

The basal part of glaciers and ice sheets has been widely studied to understand the inaccessible ice-bed interface (e.g., Lawson, 1979; Gow *et al.*, 1979; Knight, 1994; Hubbard and Sharp, 1995). Jansson *et al.* (1996) reported water pockets in the basal part of Engabreen Glacier in Norway, and argued that these pockets indicate significant water movement in the basal layers. Thus, the properties of ice pockets and their frequency of occurrence might provide insight into the properties of the inaccessible ice-bed interface of glaciers and ice sheets.

In this paper, we describe our analysis of the stable isotopes  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in and surrounding a pocket consisting of bubble-free ice in Hamna ice cliff, Sôya Coast, East Antarctica. Stable isotopic analysis is one of the most promising techniques used to study the basal part of glaciers and ice sheets. For example, this method measures the possibility of liquid water (Jouzel and Souchez, 1982) and also determines the refreezing condition at the base of glaciers and ice sheets (Souchez and Jouzel, 1984; Souchez and de Groote, 1985). Thus, this analysis should help clarify the basal hydrology of Sôya drainage, East Antarctica.

### 2. Study site and analytical procedures

The sampling site (☆) is located on the western side of Hamna Glacier, one of the outlet glaciers of the East Antarctic ice sheet, 30-km south of Syowa Station, Sôya Coast (Fig. 1). Southeast of the glacier is the ice sheet, and to the northwest is a bedrock hill

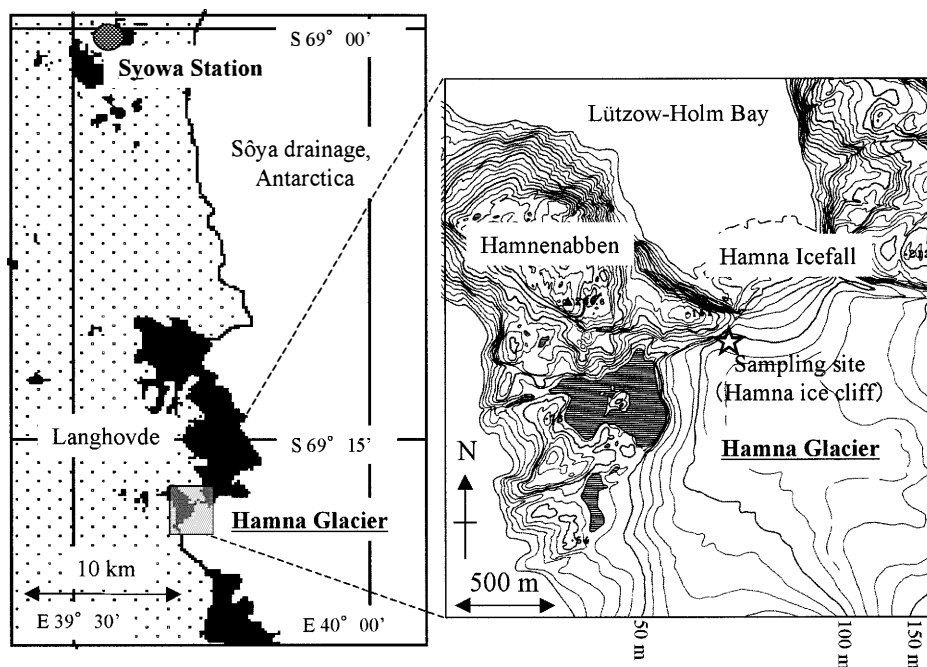


Fig. 1. Location map (left) and topographic map (right) of the Hamna icefall region at the east coast of the Sôya drainage in East Antarctica. In the location map, dotted, black and white parts indicate sea, bare rock and ice sheet, respectively. The sampling site is shown as ☆ in the topographic map on the right.

with summit elevation 141 m a.s.l.

The terminus of Hamna Glacier forms an ice cliff about 30-m high. The lower part of the ice cliff is an exposed debris-laden basal ice layer 6.8 m thick (hereafter called Hamna basal ice). Further details of the Hamna basal ice are reported by Iizuka *et al.* (2001). Above this basal ice, we observed white bubble-rich ice to the top of the ice cliff (hereafter called the Hamna Ice Sheet ice). In the Hamna Ice Sheet ice, we detected a small pocket of bubble-free ice (hereafter, the pocket). A columnar section of the Hamna Ice Sheet ice including the pocket was sampled in winter 1994 during the 35th Japanese Antarctic Research Expedition. The sample was transported frozen and stored at  $-20^{\circ}\text{C}$  in a laboratory of the Institute of Low Temperature Science, Hokkaido University, Japan.

We then analyzed the columnar section. Analyses included the stratigraphy of bubbles and stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ). A mass spectrometer (PRISM) at Toyama University was used to analyze the stable isotopes 1) for the entire pocket and 2) on 20 mesh blocks around the pocket, each of  $10 \times 10 \times 10 \text{ mm}^3$ . For the measurement of isotopic ratios, we used the  $\text{CO}_2$ - and  $\text{H}_2$ -water equilibration method with a Pt catalyst for  $\text{H}_2$ -water (e.g., Ohba and Hirabayashi, 1996). Analyses of  $\delta\text{D}$  were performed twice and averaged for each sample. Errors are estimated to be less than  $\pm 0.1\text{‰}$  for  $\delta^{18}\text{O}$  and  $\pm 1.4\text{‰}$  for  $\delta\text{D}$  (1-sigma error).

### 3. Results

Figure 2 shows pictures of the pocket. Its cross-section is a round triangular prism 30-mm on a side and at least 200 mm long (it crossed through the entire 200-mm-thick section). The pocket has solid particles but few bubbles. The solid particles are in the center and along one edge of the round triangle. The bubbly ice surrounding the pocket has spherical bubbles. Almost all crystals in the pocket and the neighboring bubbly ice were more than 10 mm across and had a similar size distribution in these two regions. The shapes of the crystals were also similar between the pocket and the neighboring bubbly ice. The large size of the crystals suggests that the pocket and the neighboring bubbly ice recrystallized, similar by to that in the Hamna basal ice (Iizuka and Watanabe, 2002).

The stable isotope values in the pocket are shown in Fig. 3. Both  $\delta^{18}\text{O}$  and  $\delta\text{D}$  show heavier values ( $-42.7\text{‰}$  and  $-338\text{‰}$ , respectively) than precipitation in the marginal region of the Sôya drainage basin, and indicate that the pocket originated from precipitation in inland regions of the ice sheet (Iizuka *et al.*, 2001). Compared to the neighboring bubbly ice with values of  $-46.5\text{‰}$  for  $\delta^{18}\text{O}$  and  $-365\text{‰}$  for  $\delta\text{D}$ , the stable isotopes of the pocket are heavier by 3.8 and 27‰, respectively.

Mesh distributions of the stable isotopes with the pocket are shown in Fig. 4. Stable isotopes in the center of the pocket are  $-42.1\sim -43.6\text{‰}$  for  $\delta^{18}\text{O}$  and  $-334\sim$

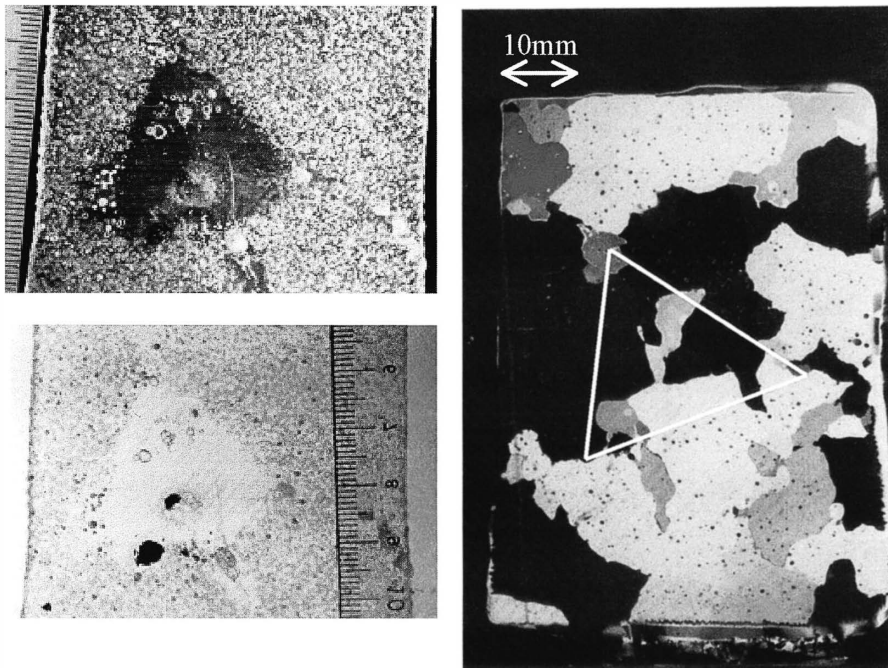


Fig. 2. Photographs of a thin cross-section through the pocket. The left photographs, which were taken by reflected (upper) and transmitted light (lower), respectively, show the bubbles and particles in the ice. The right photograph was taken by polarized light to show the crystal shapes and sizes. The triangle marked in the right photograph outlines the pocket.

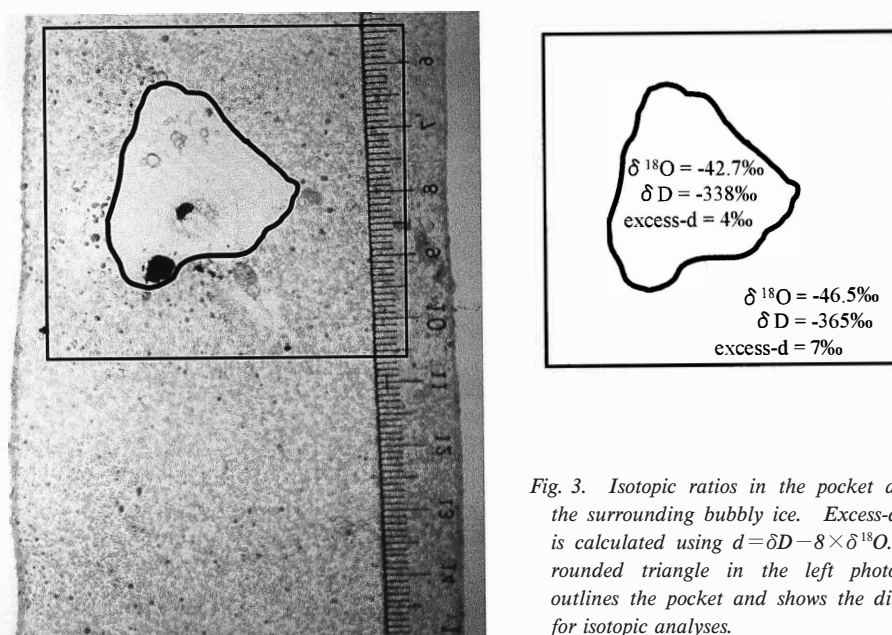


Fig. 3. Isotopic ratios in the pocket and in the surrounding bubbly ice. Excess-d (‰) is calculated using  $d = \delta\text{D} - 8 \times \delta^{18}\text{O}$ . The rounded triangle in the left photograph outlines the pocket and shows the divisions for isotopic analyses.

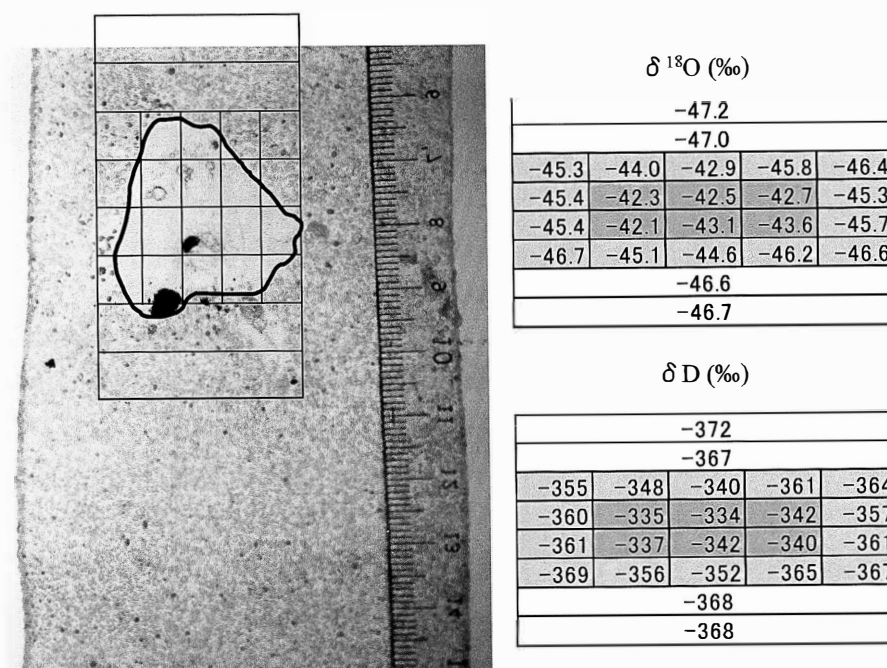


Fig. 4. Isotopic ratios analyzed by a mesh distribution. The mesh in the left photograph shows the divisions used for isotopic analyses. The dark and light gray parts indicate the center and edge of the pocket that are used in the text.

−342‰ for  $\delta D$ , and correspond to those of the values of the entire pocket that are in Fig. 3. Stable isotopes of the edge part of the pocket are −42.9~−46.7‰ and −340~−369‰, respectively. These values probably arise by mixing of the pocket (−42.7‰ and −338‰, respectively) and the neighboring bubbly ice (−46.5‰ and −365‰, respectively). The results from Figs. 3 and 4 show that the stable isotopes within the pocket are close to fixed value without  $\delta$ -value fluctuations which could be caused by Rayleigh-type fractionation.

## 4. Discussion

### 4.1. Discrepancy between the pocket and the Hamna basal ice

Iizuka *et al.* (2001) discussed the formation processes of the Hamna basal ice. The Hamna basal ice consists of alternating layers of bubble-free and bubbly ice on the order of mm to cm in thickness. The main results are 1) the bubble-free ice layers in the basal ice formed by a regelation process in an open system (Souchez and Jouzel, 1984; Souchez and de Groote, 1985), and 2) the bubbly ice layers in the basal ice with quasi-neutral values on the isotopic profile, were not affected by meltwater refreezing. To clarify the formation processes of the pocket, we discuss the differences between the pocket and the Hamna basal ice.

#### 4.1.1. Stratigraphy of bubbles

Bubbles in the Hamna basal ice are deformed into a needle shape. Iizuka *et al.* (2001) proposed that the alternating layers have been formed by the piling up of freezing layers (bubble-free ice) and non-melted layers (bubbly ice) followed by folding, and the bubble shape is caused by deformation of ice such as folding and shearing. On the other hand, bubbles around the pocket are spherical; thus, the ice around the pocket has apparently not been deformed.

#### 4.1.2. Solid particles

Both the Hamna basal ice and the pocket have solid particles, which suggests that the pocket was once in contact with the base of the ice sheet. The pocket probably formed and acquired its solid particles at or near the inland base under the Sôya drainage.

#### 4.1.3. Stable isotopes

Both the pocket and the bubble-free ice in Hamna basal ice had heavier isotopic values compared to the neighboring bubbly ice; in both cases, these isotopic differences between bubble-free and bubbly ice correspond to isotopic fractionation between water and ice (O'Neil, 1968). Therefore, the differences indicate that the pocket formed by refreezing of meltwater. The  $\delta$  values of the pocket are relatively uniform between the edges and the center of the pocket, whereas the  $\delta$  values in the bubble-free ice of the Hamna basal ice decrease gradually to those of the neighboring bubbly ice layers without any significant breaks. Meltwater refreezing processes are probably different between the Hamna basal ice and the pocket because the isotopic profiles are different between the two.

### 4.2. Formation processes of the pocket

Figure 5 is a schematic of the formation process of the pocket. The Hamna Ice Sheet ice has  $\delta^{18}O$  levels of −47 to −45‰ (Iizuka *et al.*, 2001). So, we assume that the meltwater originally in the pocket had  $\delta^{18}O$  levels of −47 to −45‰. When such water

freezes, the initially-frozen ice should have an  $\delta^{18}\text{O}$  of  $-44$  to  $-42\text{‰}$  (1.003 for fractionation coefficient at  $0^\circ\text{C}$ ), which equals the measured  $\delta^{18}\text{O}$  value of the pocket (Fig. 3). The meltwater should have frozen from the edges toward the center of the pocket because latent heat is conducted outward into the surrounding ice. So, if Rayleigh-type fractionation occurred in the pocket, the  $\delta^{18}\text{O}$  value near the center of the pocket should not be  $-44$  to  $-42\text{‰}$ . If the pocket formed by frozen ice, the values of  $-44$  to  $-42\text{‰}$  should be of the initial ice, so the discharged meltwater should have even lighter  $\delta^{18}\text{O}$  values. This discharging process means that the pocket formed by meltwater refreezing in an open system (Souchez and Jouzel, 1984; Souchez and de Groote, 1985), which is defined by the existence of input and/or runoff water during freezing. We suggest that, in the base under Sôya drainage, the pocket formed by meltwater refreezing while discharging water to the lower reach (② in Fig. 5).

Figures 3 and 5 also show the excess-d values for regions surrounding the pocket. Souchez and de Groote (1985) suggested that excess-d values of frozen ice are lighter than those of water before freezing if the system is open. The excess-d value of the pocket is lighter than that of the surrounding bubble ice. If the isotopic values of the bubble ice around the pocket are equal to those of the meltwater that formed the pocket, then the excess-d values would indicate that the pocket was formed by meltwater refreezing in an open system. This would then support the previous arguments about the importance of melting-refreezing for the formation of the pocket.

#### 4.3. Basal condition under Sôya drainage derived from the formation processes of the pocket

Recent studies on the basal hydrology of glaciers show that water under glaciers can flow 1) as a thin film at the ice/bed interface, 2) through a system of interconnected subglacial cavities, or 3) through channels into the ice/bed interface. Channels can be distinguished two types, those that cut into the ice (R-channel) and those that cut into the substrate (N-channel) (Knight, 1999). The idea of interconnected subglacial cavities does not seem correct because cavities are usually up to 10 m high and have relatively little input or output water compared to the cavity's volume. Similarly, the film suggestion does not seem correct because a film's thickness is usually less than 1 mm. The pocket's cross-sectional shape of a round triangle 30 mm on a side, indicates that the pocket was probably formed by a channel cut into the ice or into the substrate. However, if the channel were cut into the substrate (N-channel), deformation of ice would be needed to entrain the frozen channel into the bubbly ice sheet ice. Because the pocket apparently has not undergone ice deformation such as shearing, the channel that formed the pocket is probably cut into the ice, that is, an R-channel (① in Fig. 5). The edge of the pocket with solid particles (Fig. 2) might have been the bottom of the R-channel (③ in Fig. 5).

In general, the more upper part of the marginal ice having solid particles, the more inland the location where the particles were entrained into ice. Thus, the pocket probably formed further inland than the Hamna basal ice. This indicates that the basal meltwater (R-channel) originally was further inland than the regelation area that formed the Hamna basal ice under the Sôya drainage. The regelation processes of the Hamna basal ice implies that input water was supplied from further inland than the

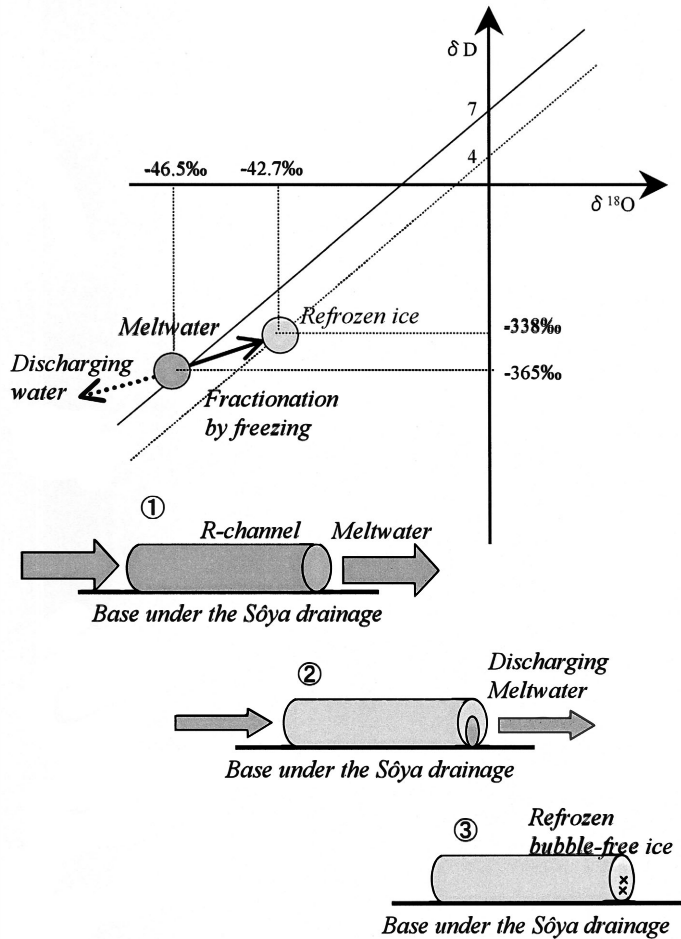


Fig. 5. Schematic of the proposed formation processes and isotopic properties of the pocket. The dark and light gray zones indicate the meltwater and refrozen ice, respectively. The black zone indicates the meltwater having a relatively heavier isotopic value caused by refreezing. The gray and black arrows show the flow of meltwater. ①: An R-channel exists under the Sôya drainage. ②: The R-channel has frozen from the outside as the water discharged. ③: When the refreezing is completed, the bubble-free ice (the pocket) was formed. Crosses in ③ show the particle positions, which are likely to have remained in the melt during the refreezing and thus are near the positions of the last section to freeze. In the plot at the top, the dark, light gray, and black circles show the  $\delta^{18}O$  and  $\delta D$  values of meltwater, refrozen ice, and discharged meltwater under the Sôya drainage as inferred from isotopic values around the pocket. The intercepts of the two lines on the ordinate are the excess-d values defined in Fig 3.

regelation area (Iizuka *et al.*, 2001). The discharged water from the refrozen area of the pocket might be the source of the input water of the Hamna basal ice.

## 5. Concluding remarks

Based on our isotope analyses, we described the formation processes of a pocket in the Hamna ice cliff. This pocket probably formed by meltwater refreezing as it discharged water to the lower reach under the Sôya drainage. The water that formed the pocket under the Sôya drainage likely flowed through channels cut into the ice (R-channel). The discharged water from the refrozen area that formed the pocket might be the input water source for the regelation area that formed the Hamna basal ice. Similar pockets consisting of bubble-free ice are probably distributed on the Hamna ice cliff. Hence, further studies of the ice cliff and the surrounding bare ice are important for understanding the basal condition under the Sôya drainage.

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