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*Scientific paper*

# Biological characteristics of dark colored material (cryoconite) on Canadian Arctic glaciers (Devon and Penny ice caps)

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***Abstract:*** Biological characteristics of dark colored material (cryoconite) collected from Canadian Arctic glaciers (Devon and Penny ice caps) are described. The cryoconite consists of mineral particles and organic matter. The amount of organic matter was 0.8–13.8% dry weight. Seven taxa of snow algae (Chlorophyta and Cyanophyta) were observed in the cryoconite. The mineral particles, the algae, the bacteria, and amorphous organic matter formed small dark colored granules (cryoconite granules). The size of the granules was approximately 0.4 mm in diameter. Microscopy of the granules revealed that the granules contain bacteria with mucus like substance, and that the surface of the granules was covered with filamentous blue-green algae. These observations suggest that the granules are formed by algal and bacterial activity on the glaciers, and that the cryoconite includes a large amount of biological products. The amount of the cryoconite per unit area on the glacier surface was generally small (mean 48 g $m^{-2}$ in dry weight). In contrast, a large amount of the cryoconite was deposited at the bottom of cryoconite holes. The small amount of cryoconite on the glacier surface means that the effect of the cryoconite on albedo reduction of the glacier surface is small.

## 1. Introduction

Impurities in snow and ice, such as airborne particles, have been shown to affect the solar heat-intake to glaciers, sea ice and seasonal snow cover (*e.g.*, Warren and Wiscombe, 1980; Warren, 1982). Dark colored material on snow and ice can reduce surface albedo and thus could accelerate melting. Therefore, albedo-reducing material with snow and ice may significantly affect the cryosphere extent in the world.

Dark colored material on the glacier surface was first named cryoconite by the Arctic explorer N. E. Nordenskjöld (1875). Recent studies have revealed that cryoconite on some glaciers contains a large amount of algae and bacteria (Gerdel and Drouet, 1960; Wharton *et al.*, 1981, 1985; Kohshima, 1987, 1989). This suggests that these microbes play important roles in the formation process of albedo-reducing material on glaciers. Since living algae and some microbes have been reported on snow and ice in various parts of the world (Kol, 1942, 1968, 1969; Kol and Peterson, 1976; Ling and Seppelt, 1993; Yoshimura *et al.*, 1997), formation of cryoconite by biological activity may be a common phenomenon on glaciers globally. In the Arctic region, several studies of cryoconite have been done (*e.g.*, Adams, 1966; Charlesworth, 1957; Gribbon, 1979). Although these studies have revealed the components of cryoconite, the precise structure and formation process of cryoconite are still not well known.

This study aims to clarify biological characteristics of cryoconite on Canadian Arctic glaciers (Devon ice cap and Penny ice cap). The composition, structure, and amount of cryoconite on the glacier surface are described. Based on detailed observations of cryoconite, the processes of its formation, and its effect on albedo reduction of the glacier surface, are discussed.

## 2. Field description and methods

Glacier surface material (cryoconite) was collected in the ablation areas of the Devon ice cap (April 1997) and the Penny ice cap (May 1997) in Nunavut, Canada (Fig. 1). On Devon ice cap, sampling was done at three sites (site A–C) of a valley outlet glacier (the Sverdrup Glacier) on the northwest part of the ice cap. The equilibrium line of the mass balance of the ice cap is at 1200 m a.s.l. (Koerner and Lundgaard, 1995). On Penny ice cap, sampling was done at five separate sites (site D–H), on Coronation Glacier on the east and on Greenshield Glacier on the west. The glacier surface of all of the sampling sites was covered with a 10–40 cm thick snow and was completely frozen during the period when samples were collected. After the snow on the glacier surface was removed, ice including cryoconite was collected on the surface and on the bottoms of cryoconite holes with an ice chisel. The collected samples were melted in plastic bags and were preserved as 3% formalin solution in 100-m*l* clean polyethylene bottles. They were transported to Japan for analysis.

The organic matter in the cryoconite was measured by the following method. After the samples were dried (65°C, 24 hour) and weighed, they were burned for 1 hour at 1000°C in an electric furnace. The percentage of weight reduction by this manipulation was measured.

The structure of the cryoconite was observed with an optical microscope, a fluorescent microscope (Nikon Optiphoto 2), and a scanning electron microscope (FE-SEM, S-800, HITACHI Co.). DAPI (4'6-diamidino-2-phenylindole) straining was used for bacteria observation with the fluorescence microscope. For scanning electron microscopy, the cryoconite was dried with a critical-point dryer (HC-80, HITACHI Co.), and was coated with carbon and Pt-Pd.

To observe the inner structure of the cryoconite, thin sections were made. The samples were dehydrated in a series of ethanol and acetone (50%, 70%, 80%, 100%, 100% of ethanol, and 100%, 100% of acetone), and then embedded in polyester resin. The embedded sample was ground by a grinder with abrasive to a thin section (approximately 0.1 mm thick). The section samples were observed with an optical microscope.

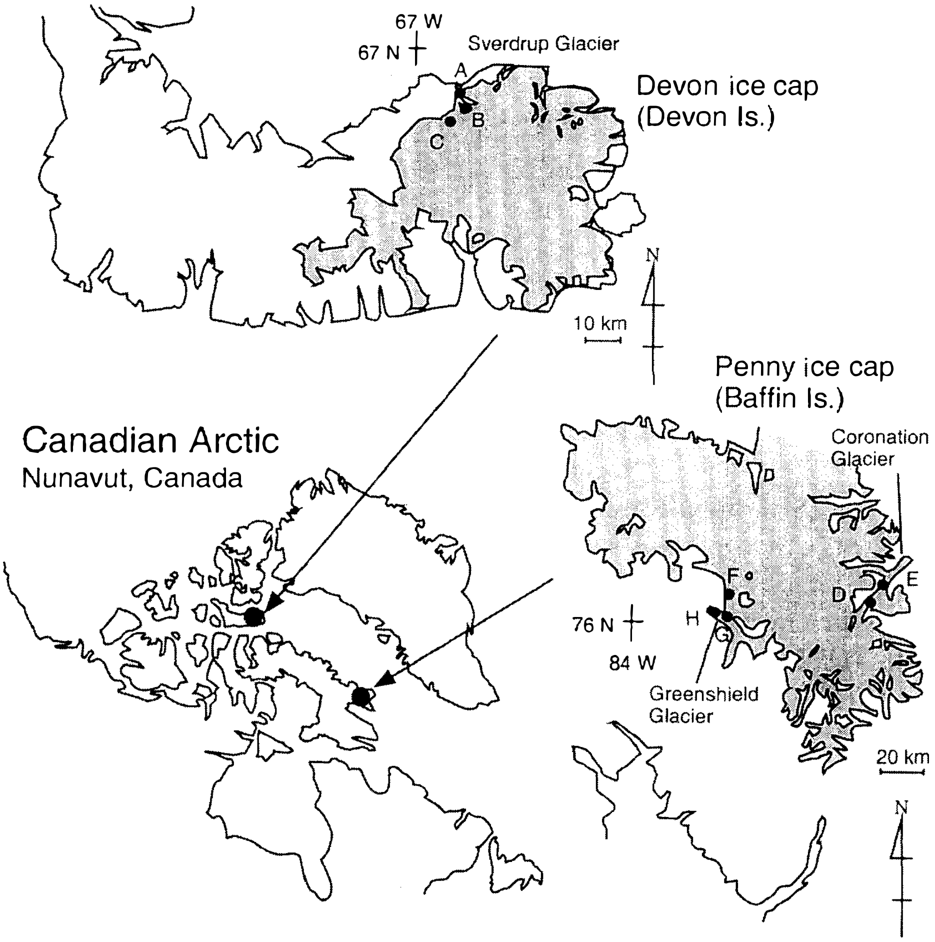

*Fig. 1. Maps of Devon and Penny ice caps in the Canadian Arctic. Sampling sites (A–H) are shown in each map.*

## 3. Results and discussion

### *3.1. Composition and structure of the cryoconite*

The cryoconite consisted of mineral particles and organic matter. Table 1 shows the percentage of organic matter (dry weight) in the cryoconite collected at each sampling site. The mean percentage of the organic matter was 8.9% (it ranged from 0.8 to 13.8%). The mineral particles included in the cryoconite are transparent or brown colored. The size of the mineral particles ranged from 30 to 330 $\mu$m.

Algae were contained in the cryoconite. The following three species of green algae (Chlorophyrta) and four species of blue-green algae (Cyanophyta or Cyanobacteria, they are referred to here as blue-green algae for simplicity) were observed.

Green algae (Chlorophyta):
*Ancylonema nordenskioldii* Berggren (Fig. 2a)

Filaments straight or slightly curved, consisting of 1–8 cells. Cells cylindrical with truncate or rounded apices, 23±5.9 $\mu$m in length, and 9.4±0.9 $\mu$m in width (mean

*Table 1. Percentage of organic matter and mean diameter of cryoconite granules of Canadian Arctic glaciers. The locations of sites A to H are shown in Fig. 1.*

| | Devon ice cap | | | Penny ice cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | A | B | C | D | E | F | G | H | Mean |
| Altitude (m) | 1065 | 700 | 300 | 790 | 670 | 960 | 660 | 450 | |
| Percentage of organic matter (%) | 4.8 | 10.5 | 10.4 | 13.8 | 11.2 | 13.8 | 6.2 | 0.8 | 8.9 |
| Size range of the granules (min-max $\mu$m) | 160<br>-840 | 90<br>-1340 | 160<br>-1020 | 170<br>-1720 | 190<br>-1090 | 140<br>-660 | 170<br>-860 | 90<br>-530 | |
| Mean size of the granules ($\mu$m) | 330 | 410 | 430 | 620 | 530 | 330 | 380 | 240 | 440 |

±standard error (SE), sample number ($n$)=25). Cytoplasm homogeneous and containing reddish pigment. Chloroplasts, bright green, and parietal with one pyrenoid. This species dominated the total algal biomass at sites G and H. This species has been reported from many glaciers in Greenland, Arctic sea ice surface, Himalaya, and Alaska (Gerdel and Drout, 1960; Melnikov, 1997; Yoshimura *et al*., 1997; Kol, 1942)

*Trochiscia* sp. (Fig. 2b)

Cells spherical 12±2.8 $\mu$m in diameter (mean±SE, $n$=16). Cell wall covered with numerous slender spines, each up to 5 $\mu$m long. Chloroplasts one to several, bright green with one pyrenoid.

*Cylindrocystis* sp. (Fig. 2c)

Cells cylindrical with rounded apices, 1 to 2 times longer than the width, 35±1.4 in length, and 15±0.4 $\mu$m wide (mean±SE, $n$=9). Chloroplasts usually two, with one pyrenoid.

Blue-green algae (Cyanophyta or Cyanobacteria):

*Calothrix parietina* Thuret (Fig. 2d)

Filaments brown, sinuous, often branched, cylindrical, long-tapering at the upper end, and 9.3±1.6 $\mu$m in wide (mean±SE, $n$=11). Trichome blue-green or brownish, cylindrical. Heterocysts brownish and spherical. This species dominated the total algal biomass at sites A, B, C, D, and F. This species has been reported in the cryoconite of Greenland (Gerdel and Drout, 1960)

Oscillatoriacean alga 1 (Fig. 2e),

Trichome blue-green and 1.6±0.3 $\mu$m in wide (mean±SE, $n$=9).

Oscillatoriacean alga 2 (Fig. 2f),

Trichome blue-green and 5.6±1.2 $\mu$m in wide (mean±SE, $n$=5).

Chroococcacean alga,

Cells blue-green, spherical, and 3.1±1.1 $\mu$m in diameter (mean±SE, $n$=16).

The algae, mineral particles, and amorphous organic matter were formed into small dark-colored granules (Fig. 3, cryoconite granules). The granules were shaped almost spherical. Their sizes ranged from 0.1 to 1.7 mm in diameter (mean: 0.4 mm, Table 1). The granules were observed at all of the study sites. The thin section of the granule shows that

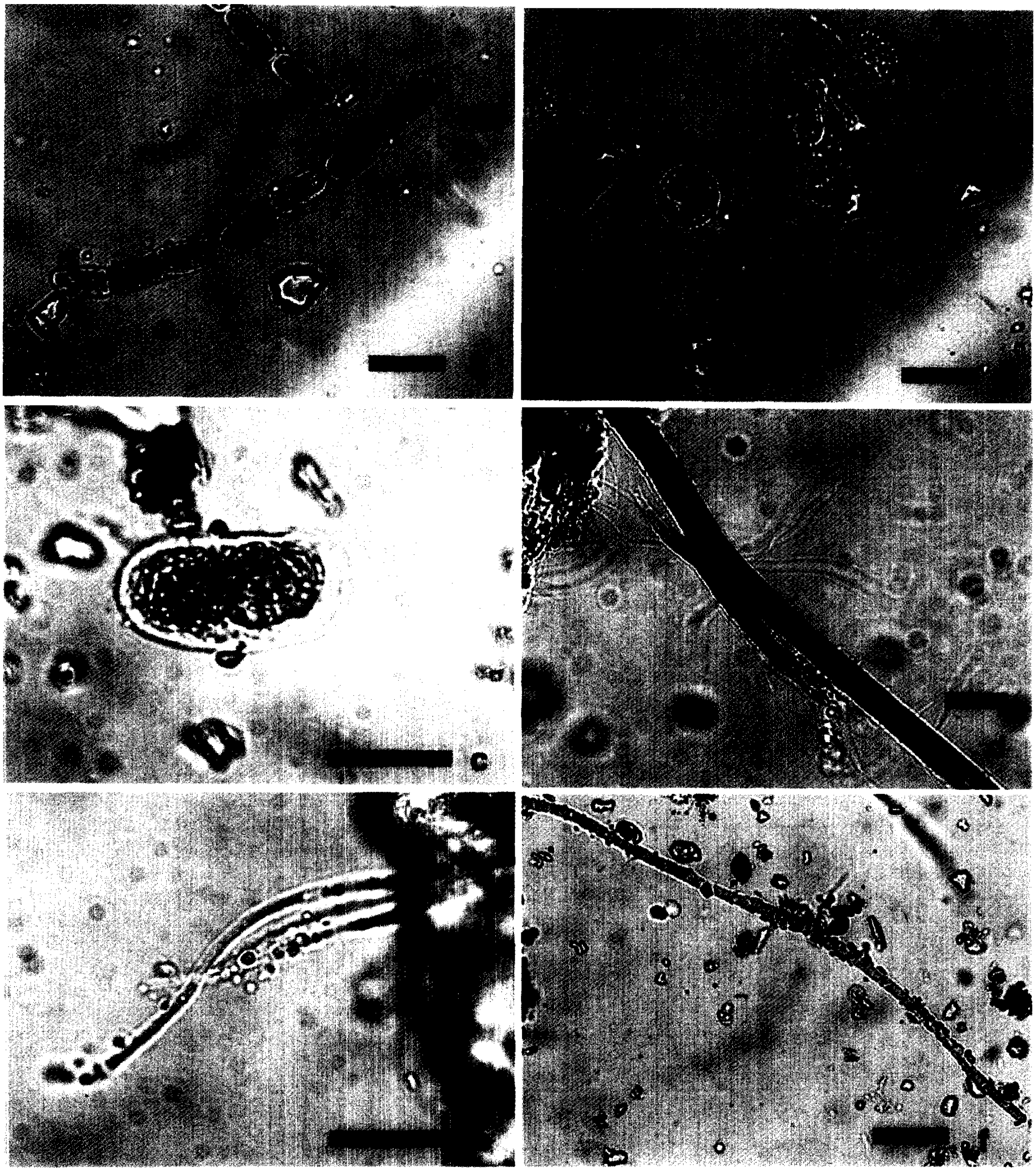

*Fig. 2. Algae observed in cryoconite of Canadian Arctic glaciers. (Scale bar = 20 μm). A Chroococcacen alga, which was also observed in the cryoconite, is not shown in this figure.*

many brown or transparent mineral particles 0.1–0.5 mm in diameter were included inside the granule and that amorphous black or brown matter (organic matter) occupied the surfaces and gaps of mineral particles of the granule (Fig. 4).

Figure 5 shows a granule observed with a florescent microscope. The surface of the granule was densely covered with Oscillatoriacean (filamentous) and Chroococcacean (coccid) algae (Fig. 5a, red colored parts). Observations with DAPI straining revealed that there were many bacteria around the blue-green algae (Fig. 5b). Figure 6 shows the granule

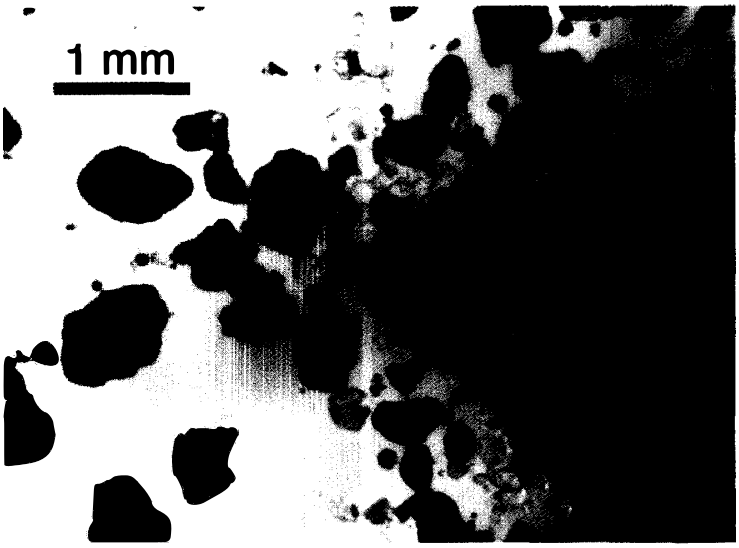

*Fig. 3. Dark colored granules (cryoconite granules) in cryoconite of Canadian Arctic glaciers.*

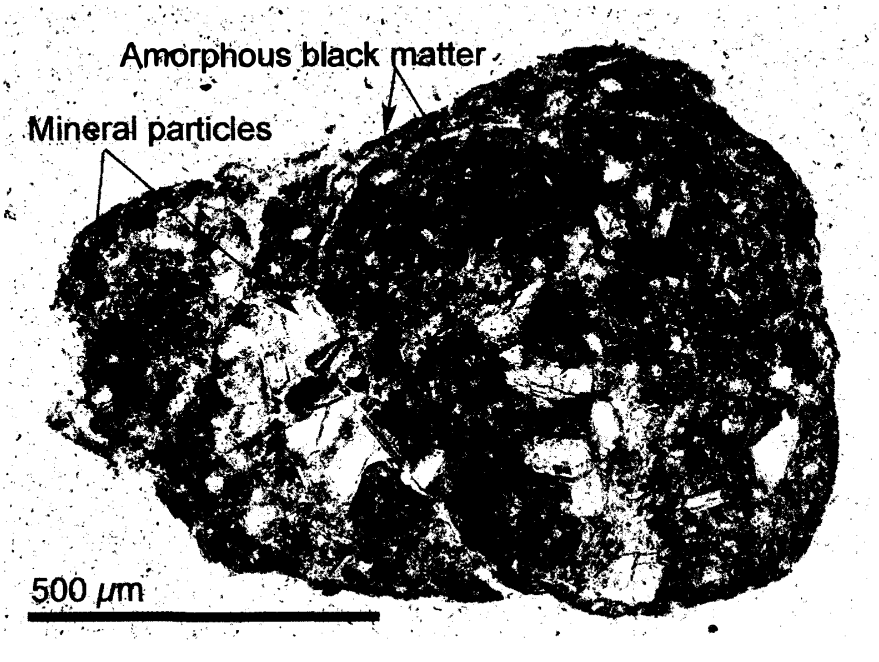

*Fig. 4. Thin-section of a cryoconite granule (Devon ice cap, site C).*

observed with a scanning electron microscope. The surface of the granule was entangled by the filamentous blue-green algae (Fig. 6a). In some granules, several cells of *Trochiscia* sp. (Green algae) are observed inside the granule (Fig. 6b, c). A large number of bacteria were observed in the granules and were often covered with a mucus-like substance (Fig. 6d).

These observations suggest that the granules are formed by algal and bacterial activity. The spherical shape of the granules is likely to be maintained by entanglement of

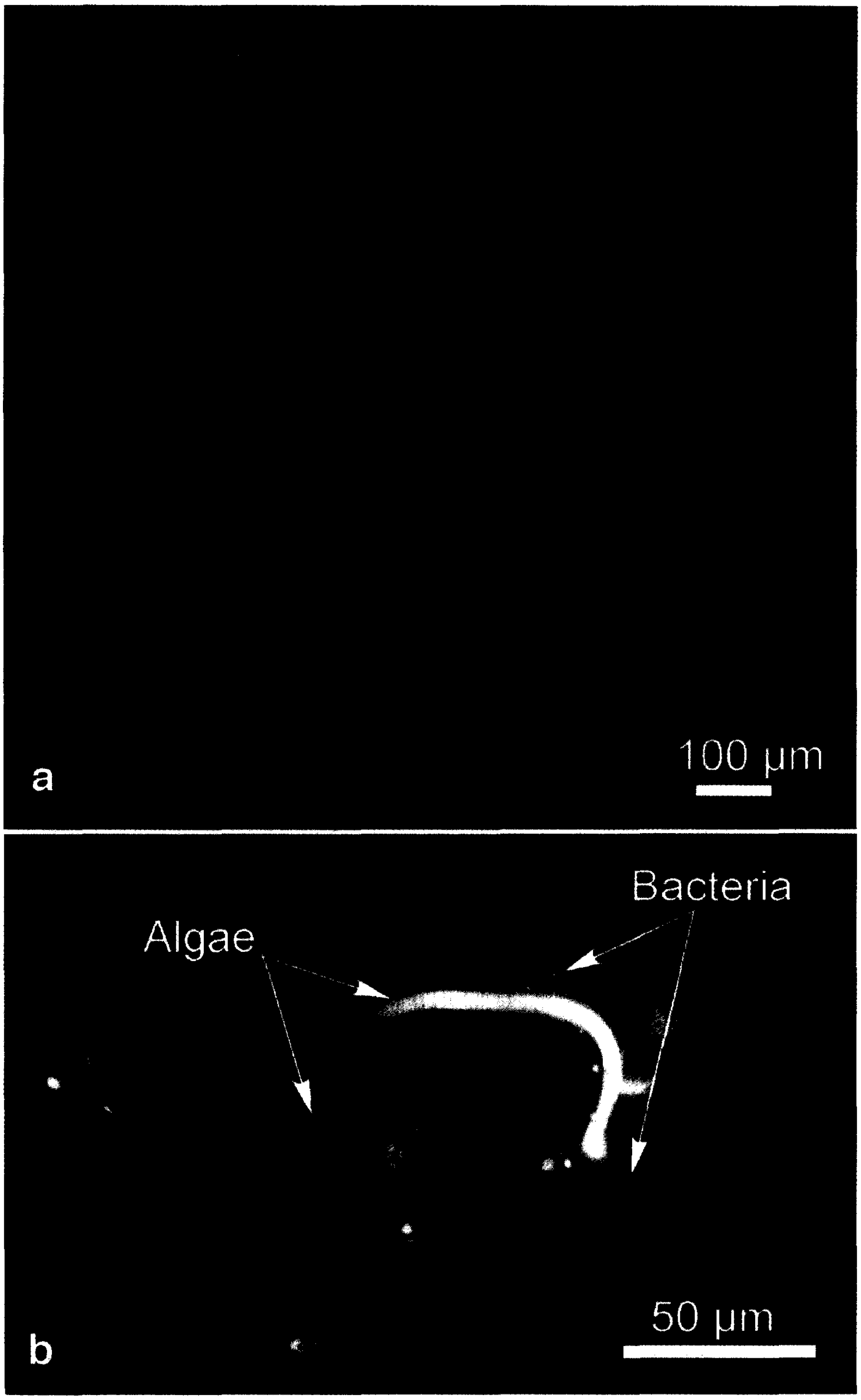

*Fig. 5.* *The cryoconite granule observed with a fluorescent microscope. a: The surface of the granule is covered with filamentous blue-green algae (red: algae with pigment fluorescent). b: Bacteria were observed around algae. (blue: DAPI strained bacteria, brown or pink: algae with pigment fluorescent)*

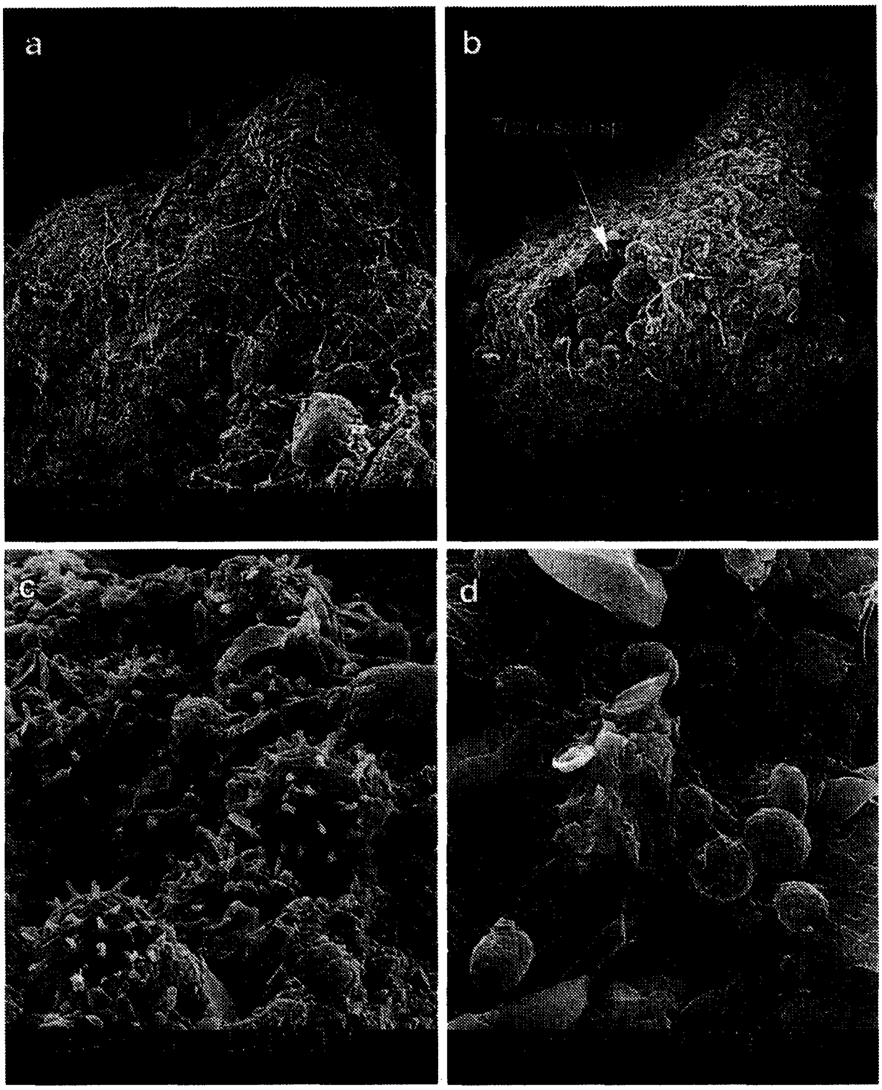

*Fig. 6. The cryoconite granule observed with a scanning electron microscope. a: The granule surface with filamentous blue-green algae (Devon), b: the surface of the granule (Penny), c: Algae buried in the granule (*Trochiscia *sp.), d: bacteria with mucus like substance in the cryoconite granule (Penny).*

filamentous blue-green algae and by adhesion of mucus-like organic matter. The size of the granule may enlarge due to growth of filamentous algae. The mucus-like organic matter may be a product of bacterial decomposition of old algae and other organic particles trapped in the granules, and/or a product of blue-green algae which have been reported by Ohtani *et al.* (1991), and by Cameron and Devaney (1970). Thus, the granule seems to be a microbial complex capable of contemporaneous photosynthesis and decomposition. This granule structure is similar to the cryoconite reported from Himalayan and Tibetan glaciers (Kohshima, 1987, 1989), suggesting that the granules are structures commonly found on glaciers globally.

### *3.2. Amount of cryoconite on the glacier surface*

The amount of cryoconite per unit area on the glacier surface was generally small (0.22–26 g $m^{-2}$ in dry weight, Table 2) except at site H (347 g $m^{-2}$). The large amount at site H is probably due to a large supply of wind-borne mineral particles (0.8% of organic matter only), since site H is close to the left bank margin of the glacier (approximately 100 m from the sampling site).

*Table 2. Amount of cryoconite per unit area on the surfaces of Canadian Arctic glaciers.*

| | Devon ice cap | | | Penny ice cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | A | B | C | D | E | F | G | H | Mean |
| Altitude (m a.s.l) | 1065 | 700 | 300 | 790 | 670 | 960 | 660 | 450 | |
| Suface ice (g $m^{-2}$) | 0.91 | 0.22 | 3.3 | 0.69 | 1.0 | 1.7 | 26 | 350 | 48 |
| Cryoconite hole (g $m^{-2}$) | 2800 | 2300 | 2100 | 1400 | 1400 | 1800 | 2700 | 4400 | 2359 |

In contrast with the small amount of cryoconite on the glacier surface, a large amount of cryoconite was deposited at the bottoms of cryoconite holes (Table 2). Cryoconite holes were observed at all sampling sites. Diameters and depths of the holes ranged from 1.0 cm to 20 cm, and from 10 to 30 cm, respectively. The cryoconite was deposited to approximately 3 mm thickness at the bottoms of the holes. Based on the density of cryoconite (dry weight per unit volume), the amount per unit area at the hole bottom (3 mm thickness) can be obtained at each sampling site (Table 2). The cryoconite amount in the holes is 1400–4400 g $m^{-2}$ (mean: 2359 g $m^{-2}$). This amount is approximately 50 times larger than on the glacier surface.

The small amount on the glacier surface indicates that the effect of the cryoconite on albedo reduction of the glacier surface is small. Albedo of the summer surface at 300 m elevation of the Sverdrup Glacier on Devon ice cap has been reported to be 40–50% (Keeler, 1964). This albedo is consistent with the albedo of clean ice (Paterson, 1994). In contrast, a large cryoconite amount (50–900 g $m^{-2}$) has been reported on the surface of a Himalayan glacier (Takeuchi *et al.*, 2000). The albedo of the Himalayan glacier surface is remarkably reduced by the cryoconite (10–30%, Kohshima *et al.*, 1993). The mean amount of cryoconite on the Himalayan glacier is approximately 6 times larger than that on Arctic glaciers (300 *versus* 48 g $m^{-2}$). This fact indicates that the effect of the cryoconite on albedo reduction is much smaller on Arctic glaciers compared with on a Himalayan glacier.

Since the cryoconite of both the Arctic and Himalayan glaciers is dominated by dark colored granules, the cryoconite amount difference between the glaciers may be due to conditions of granule formation. The composition and structure of the granules strongly suggest that the granules are formed by algal and bacterial activity on the glaciers. Therefore, physical and/or chemical conditions affecting the algal and bacterial activity may be responsible for formation of the granules. The small cryoconite amount on Arctic glaciers may be due to lower biological activity there. Cryoconite holes, which contain a large amount of cryoconite, may be the only suitable place for cryoconite formation on Arctic glaciers. As Wharton *et al.* (1985) suggested, the cryoconite at the bottoms of the holes also would have an albedo effect on glacier ablation. However, the effect is likely to be much less than that of cryoconite on the glacier surface, because the cryoconite holes found on the glacier surface were small in area, estimated at only 6.9% (Penny) and 3.2% (Devon) of the study area. Although it is still unclear which factors affect biological activity and how the cryoconite amount on the glacier surface is determined, biological activity may play an important role in cryoconite formation and albedo reduction of the glacier surface.

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