Structure and formation process of cryoconite granules on Ürümqi glacier No. 1, Tien Shan, China

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ABSTRACT. Cryoconite granules are dark-colored spherical aggregates of organic and inorganic material on glacier ice, and are commonly observed on glaciers the world over. The structure of cryoconite granules on Ürümqi glacier No. 1, Tien Shan, China, was analyzed. Granules were distributed over the entire ice surface of the ablation area, and ranged in size from 0.26 to 3.5 mm (mean 1.1 mm). The granule surface was densely covered with filamentous cyanobacteria. Microscopy of a thin section revealed various inner structures. Most granules had concentric layers of dense organic matter, which are probably derived from annual growth of the granules by the activity of cyanobacteria. The number of layers averaged 3.5 and ranged up to 7, which is likely to indicate their mean and maximum growth ages, respectively. Some granules contained two or more subgranules, showing that small granules had combined and enlarged. Such structures suggest that granule formation was mainly due to the activity of filamentous cyanobacteria, and that the granules repeatedly grew and disintegrated over a cycle of several years on the glacier.

INTRODUCTION

Cryoconite is a biogenic surface dust on glaciers that is commonly found in many parts of the world (e.g. Wharton and others, 1985). It usually accumulates at the bottom of cryoconite holes, which are water-filled cylindrical pits on the ablation ice surface of glaciers. On Asian glaciers, it also accumulates on the entire glacier surface of the ablation area (e.g. Takeuchi and others 2001b, 2005, 2006; Takeuchi and Li 2008). On such glaciers, it substantially reduces the albedo of the glacier surface and accelerates melting (Kohshima and others, 1993). The mass balance of Asian glaciers could therefore be greatly affected by the quantity and quality of cryoconite. Thus, enhancing our understanding of the formation process of cryoconite is glaciologically important.

Cryoconite consists of mineral particles, organic matter and microbes, including snow algae, cyanobacteria and bacteria. They usually form small spherical aggregates known as cryoconite granules, whose spherical shape is maintained by filamentous cyanobacteria (Takeuchi and others, 2001a,b; Hodson and others 2010). These cyanobacteria densely cover the surface of the granules and trap mineral particles inside them. There are also heterotrophic bacteria living within the granules, which are sustained by production of cyanobacteria and other algae, and/or allochthonous organic matter. This cryoconite granule structure seems to readily adapt to the cold and nutrient-poor conditions of glacial environments (e.g. Takeuchi and others, 2001b). Understanding the structure and formation process of these granules is therefore important for studies of the ecology of microbes living on glaciers. However, the formation process, dynamics and reproduction of cryoconite granules on glacier surfaces are still not well understood.

This paper describes the structure and characteristics of cryoconite granules on Ürümqi glacier No. 1, Tien Shan, China. Thin sections of granules were prepared in order to analyze the inner structure of the granules. The formation process and dynamics of cryoconite granules are discussed based on these structures.

STUDY SITE AND METHODS

The Tien Shan are one of the major mountain systems in central Asia, with peaks rising ~4000–6000 m a.s.l. Ürümqi glacier No. 1 (43°06′ N, 86°48′ E) is located in the eastern Tien Shan in Xinjiang Uygur autonomous region, China. The total area of the glacier is ~1.73 km^2. It lies between 3740 and 4486 m a.s.l., faces northwest and includes two branches (east and west), which became separated in 1994 due to glacial shrinkage (Fig. 1). The glacier is one of the most intensely studied in China. Its mass balance has been monitored since 1959, and it has retreated continuously since 1962 (Ye and others, 2005). Brown cryoconite covers most of the ice surface of the glacier and substantially reduces the surface albedo (Fig. 2; Takeuchi and Li, 2008). The amount of cryoconite on the bare ice surface ranges from 86 to 1113 g m^{-2} (mean 335 g m^{-2}, standard deviation (SD) = 211) in dry weight. The surface albedo (visible and near-infrared wavelength range) in the ice area has been 0.14 on average, significantly lower than that of the clean bare ice surface (usually 0.40).

Fieldwork was carried out from 2 to 5 June 2007. Sample collections were conducted at three sites in the bare ice area on the east branch (S1–S3). The sites chosen were visibly representative of the surface conditions around each site in terms of their surface roughness and the amount of rocky debris. The snowline during our study period was ~4000 m a.s.l. (Fig. 1). Cryoconite on the ice surface was collected with a stainless-steel scoop. To fix any biological activity, the collected samples were melted and preserved as a 3% formalin solution in clean 30 mL polyethylene bottles. All samples were transported for analysis to a laboratory of Chiba University, Japan.

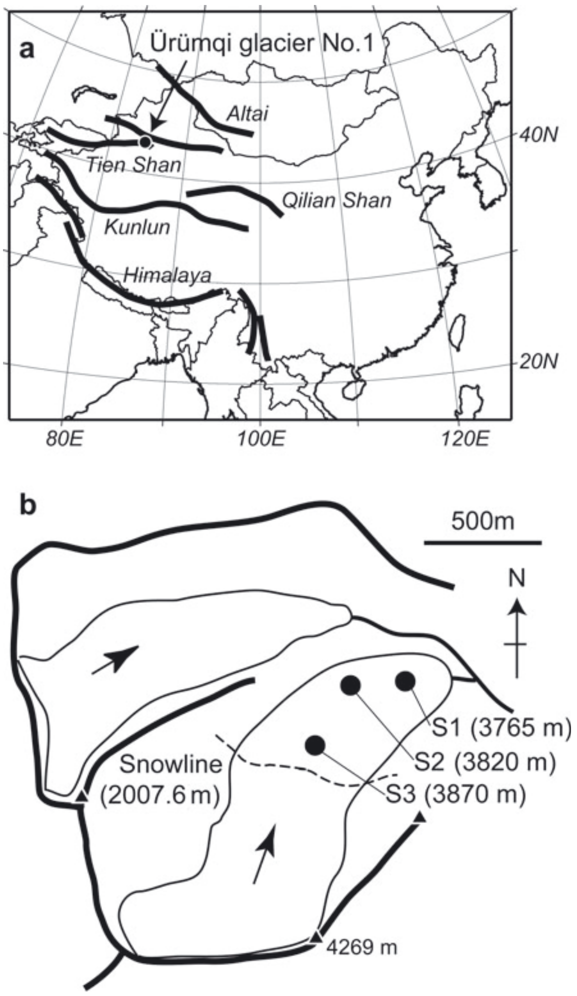

Fig. 1. Geographical location (a) and map (b) of Ürümqi glacier No. 1, Tien Shan. Sample collection sites are shown in (b).

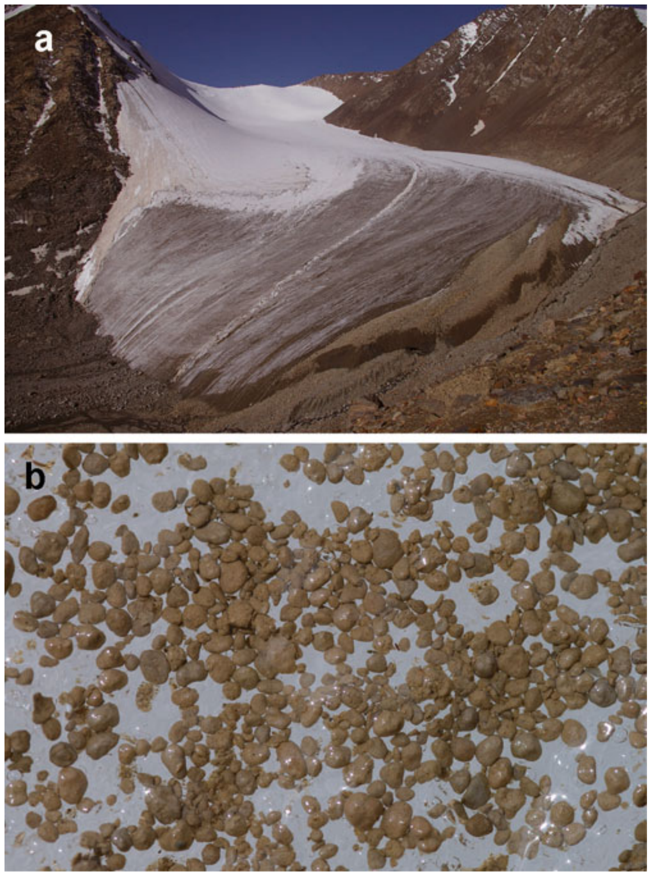

Fig. 2. Photographs of the surface of Ürümqi glacier No. 1: (a) east branches of the glacier from a moraine (25 June 2007); (b) cryoconite granules on the bare ice surface on the glacier (site S3).

Cryoconite samples were observed using optical and fluorescent microscopes (Leica MZ-12 and Olympus BX51). The size of granules (longest diameter) was manually measured on digital photographs with an image-processing application (Image J, National Institutes of Health, USA).

To observe inner structures, thin sections of cryoconite granules were made. The cryoconite granules were dehydrated in a series of ethanol and acetone (50%, 70%, 80%, 100%, 100% of ethanol, and 100%, 100% of acetone for 12 hours each) and then embedded in polyester resin (Maruto Co., Japan). The dehydration process was necessary for penetration of the resin into the cryoconite. The embedded sample was ground with abrasive to a thin section (~0.1 mm thick). The plane of the sections roughly passed the center of the granules (the equatorial plane). The section samples were observed with an optical microscope. The number of granule sections made was 186 for site S1, 165 for site S2 and 196 for site S3, a total of 547.

RESULTS

General morphology of cryoconite granules

Brown, spherical cryoconite granules were a major component of the surface dust (Fig. 3a). Florescence microscopy revealed that the surface of the granules was densely covered with filamentous cyanobacteria (Fig. 3b) consisting of at least three taxa, as noted by Takeuchi and Li (2008). The mineral particles in the dust were brown, white or transparent and were microscopically observed to range in diameter from 1.3 to 98 μm (mean 15.2 μm, SD = 8.6, sample number = 861).

The granules ranged from 0.27 to 3.5 mm in diameter. Mean and standard deviations of the size of all the measured granules were 1.1 and 0.39 mm, respectively. The most frequent size was 1.0–1.2 mm. The mean granule size differed slightly among the study sites. The largest size was at site S1 (1.24 mm), and the smallest at site S2 (1.02 mm), a difference that was statistically significant (one-way analysis of variance (ANOVA), $F = 35.6$, $P < 0.001$).

Observation of thin sections of cryoconite granules

Microscopy of cross sections revealed notable structures inside the cryoconite granules. Most parts of the sections were occupied by brown organic matter (Fig. 4). Mineral particles were found inside granules, but were generally small and occupied little space in most sections.

Most granules had concentric layers of dense organic matter (Fig. 4a). The number of layers observed per granule was 2–7 and averaged 3.5 (Fig. 5). Granules with 3 concentric layers were most frequent. The number of layers generally increased with granule size (Fig. 6). The outer layer thickness varied among different layers, parts of the layer and different granules, but was generally 0.2 mm on average. A few granules had a single dark-colored layer within each granule (Fig. 4b); this layer was composed of dark-colored organic matter and was observed in only 5 out of 547 granules.

Some granules contained two or more subgranules (Fig. 4c); these subgranules can be recognized in thin sections since each granule has an independent concentric layer structure. For example, we recognized four subgranules in the thin section of a granule shown in Figure 4c. The granules containing subgranules accounted for 147 out of 547 granules (25%). Two subgranules per granule were most frequently observed, and the maximum was ten per granule. The larger granules tended to have more subgranules. The size of this type of granule was 1.66 ± 0.45 mm (mean $\pm$ SD), which was larger than the mean of all the analyzed granules.

Some granules had relatively large mineral particles at their center (Fig. 4d). The size of these particles was 0.1–2.3 mm (mean 0.60 ± 0.46). The brown organic part took up less space than the mineral particles in the section of these granules. This structure was found in 79 out of 547 granules, and the size of this type of granule was 1.38 ± 0.43 mm (mean $\pm$ SD).

There were also granules that had no specific internal structure. In these, the section was occupied by brown organic matter and small mineral particles, but no layer structure was observed (Fig. 4e). The size of this type of granule was 1.18 ± 0.27 mm (mean $\pm$ SD).

The proportions of the total population of granules in each of the following classes were estimated (Fig. 7): type 1, a granule with concentric layers; type 2, a granule with subgranules on the inside; type 3, a granule lacking a specific inner structure; and type 4, a granule with a large mineral particle within. Type 1 was most abundant, accounting for 38.6% of all granules (Fig. 7). Types 2, 3 and 4 accounted for 26.9%, 20.1% and 14.4%, respectively, with their proportions varying among study sites. At site S2, for example, type 1 was more abundant while type 4 was less so, whereas type 4 was relatively more abundant at site S3. The differences among study sites were statistically significant ($\chi^2 = 69.8$, $P < 0.001$).

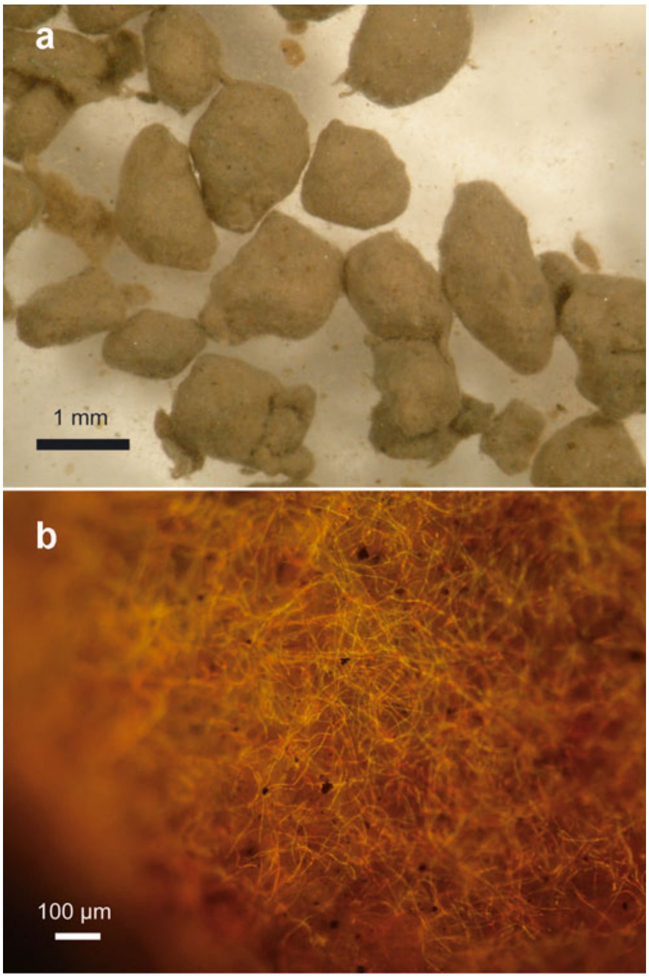

Fig. 3. Microscopic view of surface dust on Ürümqi glacier No. 1: (a) cryoconite granules collected from site S2; (b) cyanobacteria covering a cryoconite granule observed with a fluorescent microscope.

DISCUSSION

The structure of cryoconite granules indicates that they are not abiotic aggregates, but were formed by biological activity as suggested by previous studies (e.g. Takeuchi and others, 2001b; Hodson and others, 2010). Under such cramped conditions, the individual granules become entangled by filamentous cyanobacteria into a single, larger aggregate. The surface of the granules was densely covered with filamentous cyanobacteria, showing that they play a role in forming the spherical shape. The concentric layers observed in the cryoconite granules are probably derived from annual growth of the granules by the activity of cyanobacteria, that can grow on the glacier only during the melt season (usually May–September). During winter (October–April) they probably enter a resting stage on the frozen surface, since no meltwater is available on the glacier. Thus, the growth rate of cryoconite granules must vary seasonally, i.e. higher in the summer melt season and lower or subzero in winter. This seasonal cycle is probably responsible for the formation of the concentric layers of granules. The dense organic layers are likely to correspond to the layers formed by cyanobacteria in the melt season. The thickness of the layers was ~0.2 mm, which may reflect the annual growth rate of the granules.

The number of concentric layers in the granules probably indicates their growth time. Assuming that the concentric layers were formed annually, the mean number of the layers (3.5) corresponds to the mean age of the granules, i.e. 3.5 years. Similarly, the maximum number of layers (7) shows that the oldest age of the granules was 7 years. The age of granules may be physically limited. Larger granules were often partly divided, indicating that their size is limited by the binding ability of the cyanobacterial filaments and adhesive organic matter needed to maintain the granules' spherical shape. A lack of cohesiveness may also occur due to heterotrophic consumption of carbohydrates and a reduction in photosynthetic productivity. Transport- or freeze-related break-up could also occur. Large granules are probably eventually reduced to smaller fragments. Granules with three layers were the most frequently observed, suggesting that granules become fragile after 3 years.

The granules harboring subgranules were probably formed by fusion of smaller granules. On the glacier surface, cryoconite granules tended to be concentrated at the bottom of cryoconite holes or meltwater streams. Under such cramped conditions, they form aggregates with entanglements of filamentous cyanobacteria of each granule. As the cyanobacteria grow, they envelop the surface of these granules, finally forming a larger granule. Thus, these types of granules may be produced at places where cryoconite granules are densely concentrated on the glacier.

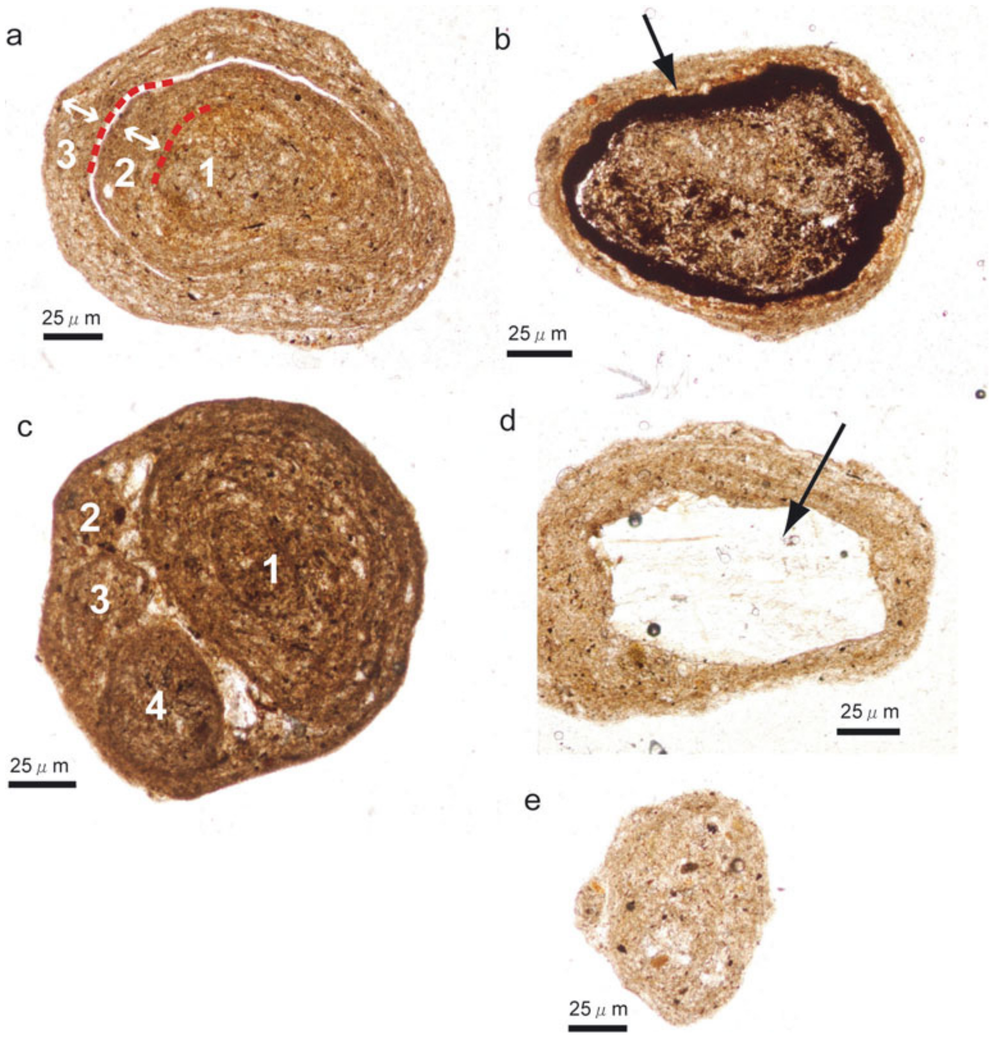

Fig. 4. Photographs of thin sections of cryoconite granules on Ürümqi glacier No. 1: (a) a granule with three concentric layers of dense organic matter (type 1); (b) a granule with a dark-colored layer inside indicated by an arrow; (c) a granule with four subgranules on the inside (type 2); (d) a granule with a large mineral particle inside (an arrow indicates the mineral particle, quartz) (type 4); and (e) a granule without specific innner structure (type 3). There are some air bubbles in the photographs, which were formed during the embedding process.

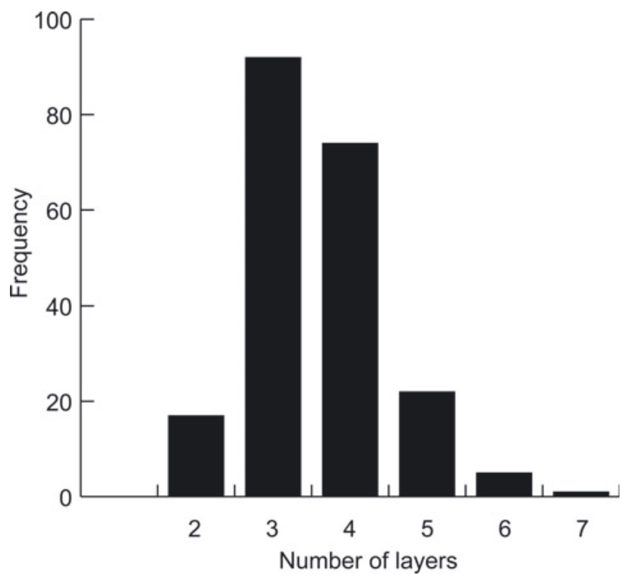

Fig. 5. Frequency of the number of layers within cryoconite granules on Ürümqi glacier No. 1.

Granules with mineral particles at their center were most likely formed by covering relatively large mineral particles with cyanobacterial filaments. The size of these mineral particles was greater than those of most of the mineral particles on the glacier. The particles of such granules ranged from 100 to 2300 μm (mean 600 ± 460 μm), while the major mineral particles on the surface ranged from 1.3 to 98 μm (mean 15.2 μm, SD = 8.6; Takeuchi and Li, 2008). These smaller particles probably consist of wind-blown dust derived from distant deserts (Sun, 2002). On the other hand, mineral particles of the granules may originate from rocky cliffs or ground surfaces around the glacier.

Though the formation process of dark-colored layers observed in a few granules (Fig. 4b) is uncertain, such dark-colored organic matter may be due to humic substances, which are highly polymerized compounds of residues remaining after the bacterial decomposition of organic matter, and which are commonly contained in cryoconite (Takeuchi 2002). A layer probably contains distinctive humic substances, which may be formed under special biological (e.g. different taxa of microbes in cryoconite) or chemical conditions (e.g. pH and/or certain soluble ions in meltwater) on the glacier. Since the dark-colored layer was observed as a single layer and in only a limited number of

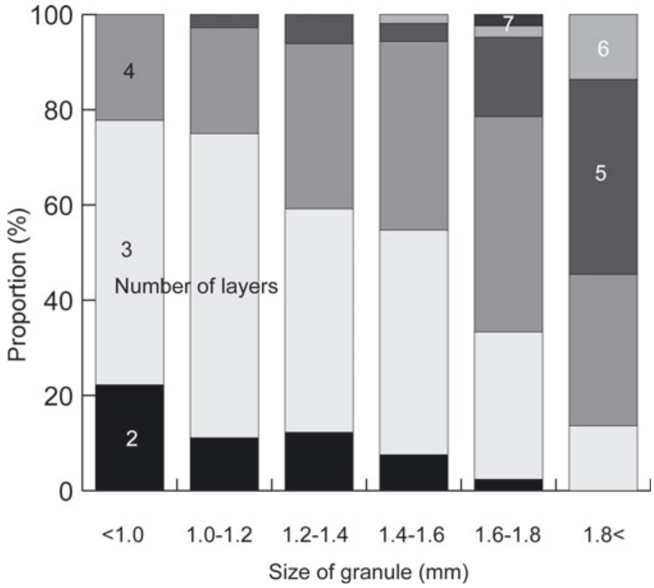

Fig. 6. The relative proportions of different numbers of layers (2–7) in cryoconite granules in each size range on Ürümqi glacier No. 1.

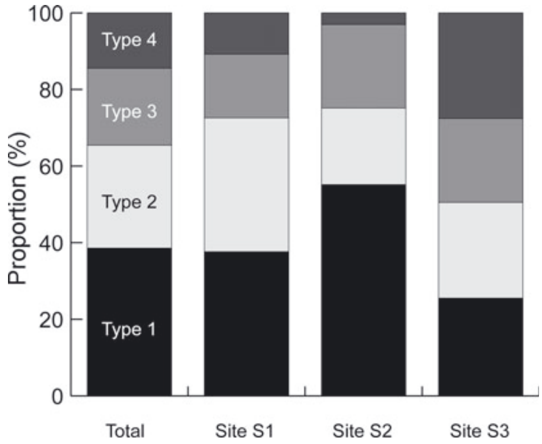

Fig. 7. The relative proportions of the four granule types among the study sites on Ürümqi glacier No. 1.

granules, such special conditions might have temporarily developed in a limited area.

Granules without a specific internal structure are likely to be observed at the initial stage of granule formation. The growth of granules probably begins from filaments of cyanobacteria attached to mineral particles, or from fragments of cryoconite granules produced by the disintegration of aged granules. These initial granules might be spherically shaped by their entrainment with cyanobacteria, and then be able in 2 or 3 years to develop into granules with concentric layers.

Based on these inner structures, the following life cycle of granules can be presumed. They grow during the melt season on the glacier via the activity of filamentous cyanobacteria that form an annual layer within the granules. They may combine with contiguous granules to produce a larger one. When granules exceed a certain size, they break up and disintegrate into smaller fragments, which subsequently regrow to form new granules. They show repeated growth and disintegration over a cycle of several years on the glacier surface.

The spherical shape of the granule is probably due to growth of cyanobacteria around a particle and physical shaping forces by the meltwater movements. If the granules remain on the same surface for a few months, cyanobacteria grow and spread horizontally on the surface and the granules would presumably become more mat-like in shape. However, mat-shaped cryoconite was not observed on the glacier, indicating that the granules keep moving by meltwater transfer down the glacier. The cryoconite at the bottom of cryoconite holes was also not mat-like but granular-shaped, suggesting that the cryoconite holes on this glacier have a short life span and repeat decay and formation.

The variation in the proportions of each type of granule among study sites may be due to physical conditions at the collection sites. The proportion of type 2 granules was relatively larger at sites S1 and S3 than at site S2. As mentioned above, type 2 granules are formed by fusions of contiguous granules and may be produced wherever cryoconite granules are densely concentrated on the glacier. Therefore, the proportion of type 2 may reflect the surface conditions at sites S1 and S3, which were probably rather static (e.g. lower surface slope gradient or less meltwater) compared with site S2. Furthermore, the proportion of type 4 granules was larger at site S3. This is probably due to the availability of large particles at the site, where there is a rock cliff adjacent to the glacier. The variation in proportions may result in differences in the mean granule size among the collection sites. The granules analyzed in this study were collected from only three sites on the glacier. It is therefore possible that the proportion and size of granules vary more significantly among different locations on the glacier. The smaller-scale conditions on the glacier surface may also affect granule formation. For example, since solar radiation is more available at the surface than the bottom, the growth conditions for cyanobacteria may be better on the surface of a thick deposit.

The morphological variability of cryoconite granules has been reported among glaciers worldwide (Takeuchi, 2002). For example, coloration of cryoconite was pale on Tibetan glaciers, but darker on Himalayan and Arctic glaciers. The size of cryoconite granules also differed among glaciers in different geographical locations, being greater on the Tibetan glaciers than on glaciers in other regions. The granules of the glacier in this study are similar to those of Tibetan glaciers, i.e. they are relatively paler in color and larger than those on glaciers in other regions. These variations may result from differences in binding ability, type, size, abundance of mineral particles, and type of cyanobacteria and other microbes in the granules. As suggested by Takeuchi and Li (2008), the cryoconite has substantially reduced the surface albedo, thus accelerating the melting of this glacier. A proper understanding of the cryoconite formation process is essential when evaluating the mass balance of glaciers. Structural analyses using thin sections help to improve our understanding of the worldwide variations in cryoconite.

CONCLUSIONS

Microscopic structure analysis of cryoconite granules on Ürümqi glacier No. 1 revealed four types of inner structure: type 1, a granule with concentric layers; type 2, a granule with subgranules on the inside; type 3, a granule lacking a specific inner structure; and type 4, a granule with a large mineral particle within. The granules were densely covered with filamentous cyanobacteria, so these structures are likely to be formed by cyanobacterial activity. These variable inner structures suggest the following life cycle of granules. They grow during the melt season on the glacier via the activity of filamentous cyanobacteria that form an annual layer within the granules. They may combine with contiguous granules to produce a larger one. When granules exceed a certain size, they break up and disintegrate into smaller fragments, which subsequently regrow to form new granules. They show repeated growth and disintegration over a cycle of several years on the glacier surface. The proportions of each structure in total granules varied among the study sites, suggesting that physical conditions at the collection sites may affect their formation. Physical and/or biological factors affecting this formation process of granules may therefore determine cryoconite coverage and albedo of the ablation surface of the glacier.

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