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Sinking of stones on glacier surface during the melting season

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Abstract

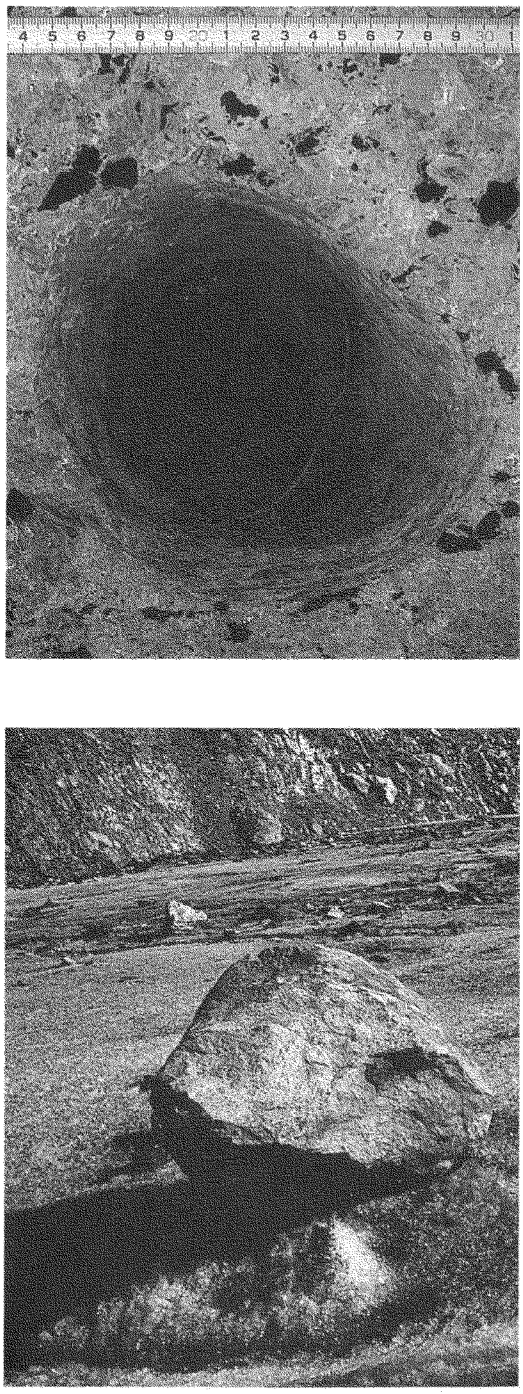
Observations and field experiments on sinking of small stones into cylindrical holes were undertaken in the ablation areas of temperate glaciers in southern Patagonia. The depths of the observed stone holes ranged from a few centimeters to 70 cm, and the diameters of the holes ranged from a few centimeters to several tens of centimeters. Water was observed inside some of the holes. We also observed that water flowed into and drained off the hole. For experiments, 26 stones and 18 coins were placed on the glacier surface. Movement of stones relative to the glacier surface was measured during 16 days in November and those of coins during six days in December, 1993. The stones sank into ice, while occasionally rose apparently in a short period. Speeds of sinking or rising of stones ranged from a few centimeters up to 8.2 cm per day. The speed has a negative correlation with the albedo of stones. It was suggested that the shortwave radiation to the glacier surface accelerated the stone sinking and the turbulent heat flux to the surface accelerated the stone rising.

1. Introduction

During the melting season, small stones are often found at the bottom of cylindrical holes or on the top of ice mounds on the surface of ablation areas of glaciers (Fig. 1). We call this hole a *stone hole*. For example, Sharp (1988) mentioned this phenomenon in his book. These stone holes and ice mounds are considered to be formed as a result of different melting rates between glacier surface and ice beneath the stones. This phenomenon is seen not only on glaciers but on lake ice (Toukairin, 1977) and snowcovers. These phenomena are similar to well-studied phenomena that a debris layer on glacier surface enhances or reduces the ablation of glacier ice, and that fine sand and organic material on the glacier surface make a hole called *cryoconite hole* (*e.g.* McIntyre, 1984). However, stone holes have been little studied.

Ablation rates of debris-covered glaciers depend on physical properties and thickness of the covering material (Nakawo and Young, 1981). Mattson *et al.* (1992) showed that a layer thinner than about 3 cm enhanced the ablation and a thicker layer reduced the ablation. In the case of debris-covered glaciers, the debris layer can be assumed to be a horizontal plane. On the other hand, in the case of the stone hole or the ice mound, the covering material (stone) is not planar. This makes it difficult to understand the holes and the mounds.

Cryoconite holes are also formed as a result of different melting rates between glacier surface and ice beneath the sand or organic material (*e. g.* Gribbon, 1979). Not only meteorological energy but also biological energy made by organic material can develop cryoconite holes (McIntyre, 1984). Black materials scattered around the stone hole in Fig. 1 (a) may seem to be the initial states of cryoconite holes. McIntyre (1984) mentioned that cryoconite holes are filled with water and formed with fine particles, of which diameters are on the order of 0.1 mm. On the other hand, as we observed, many stone holes are not filled with water and formed holes with stones, of which diameters are on the order from 1 cm to 10 cm. Though stone holes and cryoconite holes are different phenomena, they are considered as similar from the point that both holes are formed as a result of different ablation



b

Fig. 1. (a) A stone at the bottom of a stone hole and (b) at the top of an ice mound on the surface of Moreno Glacier. The height of the stone in (b) is about 1 m. Substances scattered around hole in (a) seemed to be fine particles of sand.

rates between glacier surface and ice beneath substances.

In the summer 1993, on three temperate glaciers in southern Patagonia, we made some preliminary observations on the features of stone holes such as their depths and diameters. We also carried out experiments on the formation processes of stone holes on the glaciers. In this report, we present the results of the observations and experiments.

2. Observations

Observations on general features of stone holes were carried out in November and December 1993, on flat space of ablation areas of Moreno Glacier, Upsala Glacier and Tyndall Glacier, southern Patagonia. Geographical features of these glaciers are reviewed by Naruse and Aniya (1995). Meteorological studies at Moreno Glacier and Tyndall Glacier were also undertaken during the same period of our study (Takeuchi *et al.*, 1995a, 1995b). The mean values of meteorological conditions during the experimental period at these two glaciers are shown in Table 1. Meteorological conditions on Upsala Glacier are considered as similar to Moreno Glacier, because Upsala Glacier lies near Moreno Glacier.

On Moreno Glacier, many stones of various sizes were scattered, that made the surface look dark. More stone holes or ice mounds were seen in the area that looked white than in the area that looked dark. Dirt cones of various sizes are also scattered in the same part of Moreno Glacier. Mean albedo of seven dirt cones measured at 2 cm above the top of them was 0.05. Surfaces of some dirt cones were wet and some were dry. In Moreno Glacier, dirt cones seemed to distribute mainly near the bank and, on the other hands, stone holes mainly central part.

Table 2 shows features of the observed stone holes at Moreno Glacier. Depths of the holes were a few tens of centimeters and the maximum was 70 cm. The diameters of the holes ranged broadly from a few centimeters to 50 cm. We did not find an obvious relationship between the diameter and the depth of the stone holes. Water was observed inside some of the stone holes.

The direction of stone sinking was not only vertical but occasionally inclined by a few tens of degrees from the vertical line. For instance of an extreme case, it was observed at Upsala Glacier that tree leaves sank perpendicular to the slope of serac in-

Table 1. Mean meteorological conditons at Moreno Glacier and Tyndall Glacier. Each site of meteorological observation was located about 10 m away from each experimental site. The data in this table were collected by Takeushi *et al.* (1995a).

	Moreno Glacier	Tyndall Glacier
Observation period	November 12-27, 1993	December 9–17, 1993
Global radiation (MJ/m^2d)	20.5	20.2
Air temperature(℃)	7.9	5.1
Wind speed (m/s)	4.9	6.6
Ablation of glacier surface (mm/d)	49	60

Table 2. Data of stone holes and stones at their bottoms (Moreno Glacier). Depth and water level were measured from the glacier surface to the upper surface of stones. First three holes were observed on November 22 and others on November 17, 1993. In the column of diameter, expressions of AxB denote two sides of stones ; the smallest side (A) and the largest side (B).

Depth of Hole	Diameter of Stone	Water Level
cm	cm	cm
13	1.8x3.2	4.5
14	2x2	4
2.3	3.8x5.7	0
27	1.5x1.5	0
41	3x3	0
26	4x4	7.5
15	5x5	0
25	6x6	0
45	7x7	0
32	15x15	8
35	5x5	0
14	6x6	0
65	8x17	42
70	48x30	60

clined at about 40 degrees and direction of their holes seemed to coincide with the solar angle.

Stone holes were also often seen at the beds of shallow water streams on the surface of Moreno Glacier. At the stream beds, honeycombed ice structures made with small stones were observed. These structures seemed to form at the bed shallower than several centimeters.

3. Experiments

In order to understand the formation processes of stone holes, we carried out field experiments during 16 days starting from November 11, 1993 at Moreno Glacier and during 6 days starting from December 12, 1993 at Tyndall Glacier. Sites of the experiments were located on flat expanse of the ablation areas of the glaciers. The sites were about 10 m away from the meteorological observation sites at both glaciers.

As illustrated in Fig. 2, a_b denotes the thickness of

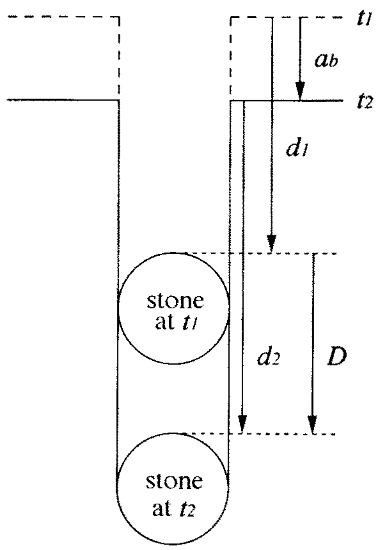


Fig. 2. Schematic diagram of stone sinking with the development of a cylindrical hole. Broken line and solid line show the glacier surface at time t_1 and t_2, respectively. a_b indicates the ablation of glacier ice, and d_1 and d_2 are defined as depths at t_1 and t_2, respectively. D is a displacement, obtained from $D = d_2 - d_1 + a_b$.

melted glacier ice in the period from time t_1 to time t_2. d_1 and d_2 are depths of a hole at t_1 and t_2, respectively. D $(=d_2-d_1+a_b)$ is a displacement. We define a displacement speed as $D/(t_2-t_1)$. The vertical axis is taken to be positive downward. We measured d_1, d_2 and a_b, and then we calculated D. a_b was measured with a stake set up deeper than 50 cm in the glacier ice (Takeuchi *et al.*, 1995b).

At Moreno Glacier, we aimed at finding out the relationships between the displacement speed and meteorological conditions or the sizes of stones. 26 stones found on the glacier surface were placed being separated each other. We measured d_1, d_2 and a_b every day. After the experiments, we measured the weight of the stones by a spring balance and the sizes of the stones by a ruler. The thickness was defined as the largest value of the vertical dimension of a stone placed on the glacier. Their weights ranged from 3 g to over 20 kg, and their horizontal areas ranged from 92 mm^2 to 0.14 m^2 with the thicknesses ranging from 3 mm to 178 mm. The surface temperature of stones was measured by an infrared thermometer once in daytime during six days. It ranged from -0.5 °C to 21.9 °C.

At Tyndall Glacier, we used 18 coins. To examine the dependence of the displacement speed on the albedo and the material, three types of coins (1 yen coin of Japan, 5 peso and 10 peso coins of Chile) painted black with marker and three types of unpainted coins were used. To examine the dependence on depth, six coins were placed for each on the glacier surface, and at the bottoms of about 80 mm and 180 mm deep cylindrical holes, which were dug with a hand drill, respectively.

4. Results of experiments

Daily changes in the depths (d) of five representative stone holes are shown in Fig. 3. These five stone holes are selected to show the variety of behavior of stone holes. The deepest was 147 mm on November 24. Stones did not only sink but occasionally rose apparently. A maximum of displacement was 82 mm in a day. Daily change in the depth, d_2-d_1 $(=D-a_b)$, depends on the difference in the melting rates between the glacier surface and of the ice beneath the stones.

Firstly, we consider the effect of stone size on the displacement of the stones. A mean displacement speed of each stone over a long period under various meteorological conditions is considered to be a quantity that reflects well the features and the heat characteristics of the stones. Relationship between the stone thickness and the mean displacement speed is shown in Fig. 4. They have a positive correlation within a reliability of 95 %. This trend indicates that, if we assume the heat transport through the stone sides was zero, the larger amount of heat was transferred to the bottom through a thicker stone than a thinner stone. Therefore, this trend is inconsistent with a one-dimensional heat-transfer model, that

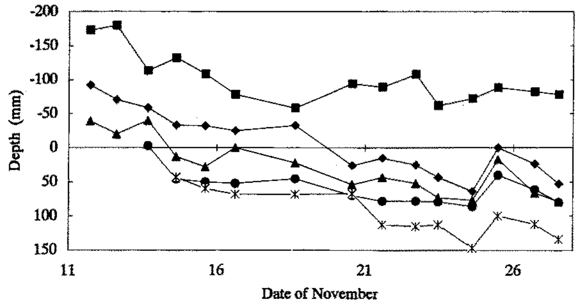


Fig. 3. Daily changes in depth of stone holes (Moreno Glacier). Each symbol denotes each stone placed on the glacier. Three stones were placed on November 11 and others on November 13 or 14. The initial depth was equal to the thickness of a stone. The minus sign of the depth indicates that the upper surface of a stone was above the glacier surface.

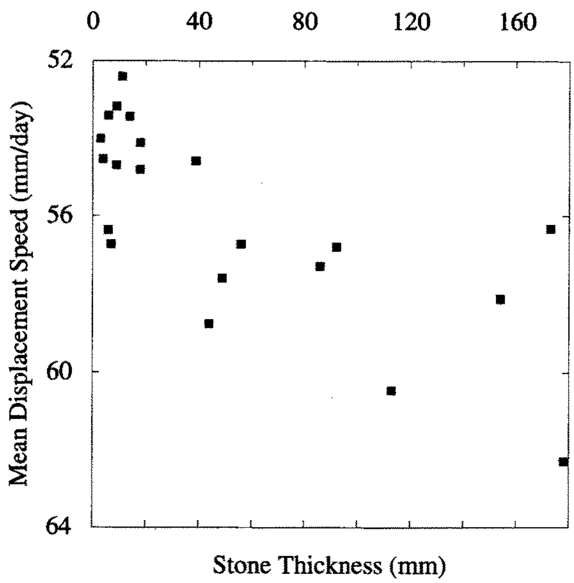


Fig. 4. Relationship between the stone thickness and the mean daily displacement speed during 16 days (Moreno Glacier).

explains the heat balance at the debris-covered glacier surface (*e. g.* Nakawo and Takahashi, 1982). However, we note that, in this experiment, different kinds of stones were used and other factors, for example specific heat and thermal conductivity, may possibly control the sinking. We also examined the dependence of the mean displacement speed on the weight, horizontal area and mean surface temperature of stones, respectively. However, no significant correlations were observed.

Secondly, we mention the dependence on albedo, material and depth of stones. In Fig. 5, we show the displacement speeds of the coins placed at different depths. At three depths, the remarkable difference among three types of coins, that were made of different materials was not observed. Around 25 mm and 90 mm of $(d_1+d_2)/2$, the mean displacement speed of unpainted coins is smaller than that of black-painted coins, but, around 180 mm, there is little difference between them. The albedo of the black-painted coins is much smaller than that of the unpainted coins. Therefore, the displacement speed of coins or stones has a negative correlation with the albedo in shallow holes, however, this effect became small in holes deeper than several of centimeters.

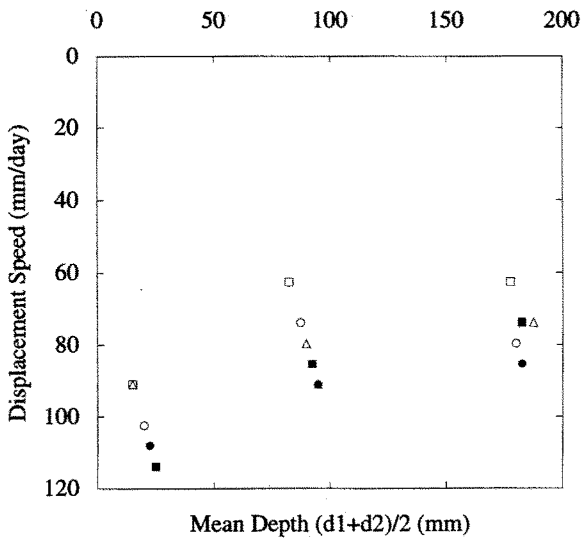


Fig. 5. Displacement speed of unpainted coins (open symbols) and black-painted coins (solid symbols) at the various depths (Tynball Glacier). Square, circle and triangle show 1 yen, 5 paso and 10 peso coins, respectively. Six coins (3 unpainted and 3 painted coins) were placed at each depth : on the glacier surface, and at the bottoms about 80 mm and 180 mm beep cylindrical holes, respectively. Some symbols are overlapped on the graph. The measurerent was carried out from 13 : 25 on December 13 to 10 : 30 on December 14 1993.

Finally, we mention the dependence on meteorological conditions. We examined the relationship among the daily change of depth, d_2-d_1, the daily shortwave radiation, SR, and the daily turbulent heat flux to the glacier surface, H_t, by a multiple linear regression in a form of

$$d_2-d_1=\alpha_1 SR+\alpha_2 H_t. \tag{1}$$

We applied the equation (1) to the 90 data sets $\{d_2-d_1, SR, H_t\}$ at Moreno Glacier ; SR was directly measured and H_t was calculated using a bulk aerodynamic approach (Takeuchi *et al.*, 1995a, 1995b). As seen in Fig. 4, d_2-d_1 $(=D-a_b)$ depends on the thickness of stone. Therefore, in order to standardize the thickness, we selected seven stones on the order of 1 cm of thickness. Also, to eliminate the effect of albedo of stones, data of d_2-d_1 in holes deeper than 40 mm were used for the analysis. Under a reliability of 90 %, these parameters were estimated as follows :

$$\alpha_1=0.46\pm0.40 \text{ (mm/MJ)}$$
$$\alpha_2=-0.83\pm0.65 \text{ (mm/MJ)}.$$

Accordingly, the possibility of $\alpha_1\leq 0$ and $\alpha_2\geq 0$ are excluded under a reliability of 90 %. Hence, the shortwave radiation accelerates sinking and the turbulent heat flux accelerates rising.

5. Discussions

At Moreno Glacier, we observed the behavior of water inside the stone holes. Figure 6 shows the daily changes in depth and water level of a stone hole. It indicates that water flows into and drains off the hole. This was also observed at the other five holes. McIntyre (1984) pointed out an effect of water on the development of cryoconite holes. Though we can not find out an obvious correlation between variations in the depth and the water level, we consider an effect of behaviors of water on the developments of the stone holes. Koizumi and Naruse (1994) performed laboratory experiments and showed that water streams with the temperature slightly higher than 0 °C enhanced considerably the growth rate of water channels within ice. In summer, the temperature of water on the glacier surface and the stone surface can be considered as slightly higher than 0 °C due to absorption of the strong shortwave radiation. If the water flows into the holes, the displacement speed might be pos-

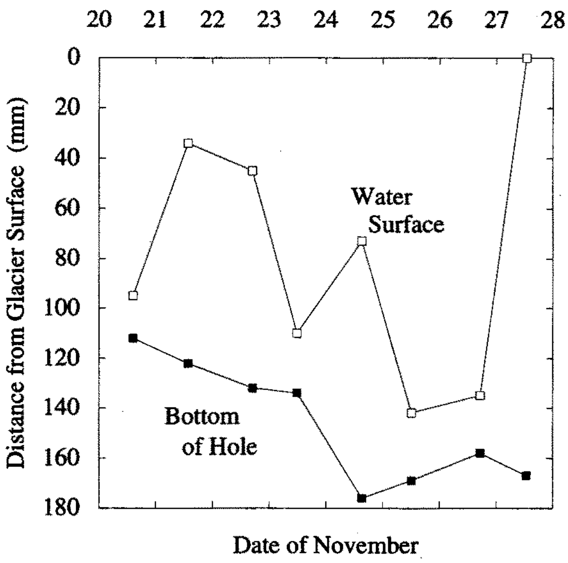


Fig. 6. Daily changes in depth (solid square) and water level (open square) of cylindrical hole (Moreno Glacier). The thickness, and the largest and smallest sides of the stone were 14 mm, 18 mm and 43 mm respectively. The stone was placed on November 21, 1993 at the bottom of a 112 mm deep cylindrical hole.

sibly accelerated by the water. For quantitative estimation of this effect, detailed observation on the flow and temperature of the water are needed.

Sinking speed of a stone due to the plastic deformation of ice, U, was discussed by Nagata (1977). Using his result, we can estimate a maximum value of U to be an order of 10^{-7} mm/day for the typical size stones in our experiments. The observed displacement speed mentioned above was an order of 1 mm/day. Therefore, we can neglect this effect obviously.

6. Conclusions

We made observations and field experiments on the stone sinking into the glacier ice during the melting season. Stones do not only sink but occasionally rise apparently. Stones moved into ice in a short period of time, up to 8.2 cm in a day. The stone sinking depends on the difference in ablation rates between the glacier surface and ice underneath the stones. The displacement speed has a negative correlation with the stone albedo. Shortwave radiation accelerates sinking and turbulent heat flux accelerates rising. For quantitative discussion, detailed observations and experiments with standardized samples are needed.

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