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Processes of failure and collapse of an ice-dam at Glaciar Perito Moreno, Patagonia, in March 2004

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Abstract

An ice-dam of about 145 m high and 300 m wide was formed in September 2003 at Glaciar Perito Moreno, southern Patagonia, blocking the water flow from the tributary arms, Brazo Rico-Sur (BRS), to Lago Argentino. The water level of BRS continued to rise at an almost constant rate of 5 cm/day reaching the highest at 9.35 m above the normal lake level on 11 March 2004, *i.e.* about 35 m lower than the floatation level. Detectable drain of water from BRS through the ice-dam started on 11 March, which was followed by a spectacular collapse of the dam on 14 March. A total of 0.99 km^3 of water was drained during 3.5 days with the peak discharge of 8,400 m^3/s on 14 March. Analyses of water level changes and studies on the development of a water channel within a temperate ice suggest that the weak water leak may have commenced by the beginning of March through a narrow subglacial channel, which had subsequently been enlarged due to ice melting to the order of meters in diameter in about 15 days. This event was apparently similar to but quite different from the huge outburst in Russell Fjord next to the tidewater calving Hubbard Glacier, which was triggered by water flow over the moraine-dam and drained 3 km^3 of water within 30 hours.

1. Introduction

Glaciar Perito Moreno is one of the most spectacular calving glaciers in fresh-water lakes in Patagonia, representing thereby one of the major tourist attractions in Argentina. The glacier has been behaving in a unique manner during recent decades, because it has been in a near-steady state in the last half century (Aniya and Skvarca, 1992), in contrast to a large number of significantly retreating glaciers in Patagonia (Naruse *et al*., 1995a; Aniya *et al*., 1997). The characteristics and recent glacier behaviours were described by Aniya and Skvarca (1992), Skvarca and Naruse (1997), Rott *et al*. (1998), Stuefer (1999) and Stuefer *et al*. (2007).

Nourished by high snow accumulation on the ice-field of Hielo Patagónico Sur, the ablation area of Glaciar Perito Moreno represents a large valley-type glacier about 15 km long and 4 km wide. The terminus of the glacier calves into the southwestern arm of Lago (lake) Argentino (LA), namely into Canal de los Témpanos (CT) and Brazo Rico (also called Lago Rico), and the glacier front reaches currently the opposite bank (Península Magallanes: PM) at 50°30'S and 73°00'W (Fig. 1).

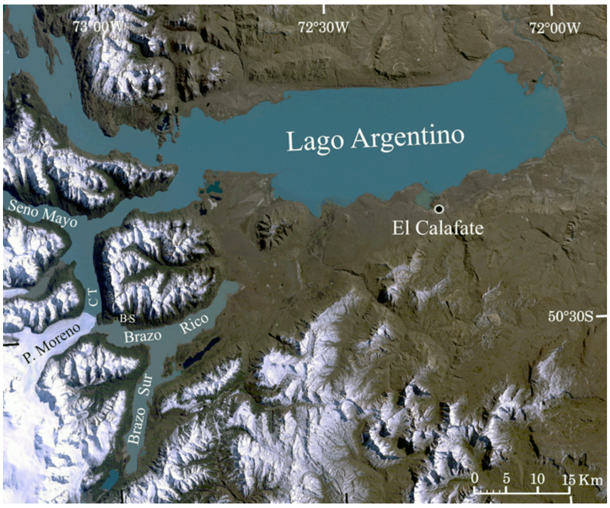

Fig. 1. Landsat 5 image (Mar. 21, 2001) showing Glaciar Perito Moreno and the surrounding area. CT: Canal de los Témpanos. B-S: Bajo de las Sombras.

According to Liss (1970) and other information, Glaciar Perito Moreno advanced steadily from the end of the 19th century to 1917, the year when the closure of the channel between the glacier front and PM was first documented. During about 60 years from the mid 1930s to the mid 1990s, the closures of the channel were recorded about 14 times without any clear cycles

(Skvarca and Naruse, 1997). It is considered that some of these channel closures may have resulted in building ice-dams at the glacier front, and their ruptures may have caused the outbursts. The record of water discharge of Río Santa Cruz, draining eastward from LA**,** showed significantly high water discharges in 1960, 1963, 1966, 1980, 1984 and 1988 (Fig. 2). We believe that these high peaks should correspond to the outbursts from the ice-dammed lake, Lago Rico.

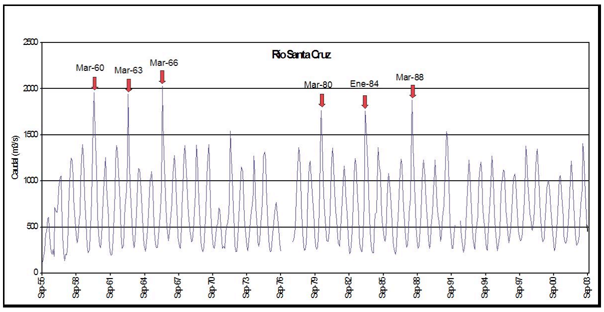

Fig. 2. Fluctuations in water discharge of Río Santa Cruz, drained eastwards from the eastern end (near El Calafate) of Lago Argentino, from September 1955 to September 2003. (Courtesy of Sub-secretaría de Recursos Hídricos, Argentina)

At the mid-reach of the glacier, we repeatedly measured a cross-profile of the glacier surface by means of distance surveys since 1990 (Naruse *et al*., 1995b; Skvarca and Naruse, 1997), finding out that in 1990-99 the surface level remained very stable without thickening or thinning. However, between 1999 and 2002, the glacier was found to be thickening (Skvarca *et al*., 2004). We considered that the thickening trend at the middle reach in 1999-2002 might have influenced the glacier advance in 2003, which resulted in the formation of an ice-dam in 2004 (this study).

Major contents of this article are based on a paper entitled "Collapse of the ice-dam of fresh-water calving Glaciar Perito Moreno, southern Patagonia in March 2004" presented by R. Naruse and P. Skvarca at the International Symposium on Dynamics in Glaciology organized by International Glaciological Society, which was held in Ireland, August 2008.

In the present study, we call the crash and burst of an ice-dam 'collapse', and the condition during a stage from the beginning of detectable weak water leakage through the ice-dam till the collapse 'failure'.

2. Formation of the Ice-dam in 2003-2004

In September 2003 the glacier front has reached the opposite bank and impeded the water draining from the southwestern arm (Brazo Rico-Sur: BRS) to CT of LA, which drains ultimately via Río Santa Cruz to the Atlantic Ocean. The water level of the BRS lacustrine system continued to rise by several cm per day until March 2004, when the water level reached the highest at 9.35 m above the normal level (Skvarca and Naruse, 2006). Figure 3 shows the rise in water level measured daily at the Bajo de las Sombras (B-S) pier on the northern coast of BRS (O. Kloster, unpublished data). On 14 December 2003, the BRS water level was 4.2 m higher than CT, which is on the leeside of the glacier tongue, as measured by the conventional trigonometric survey.

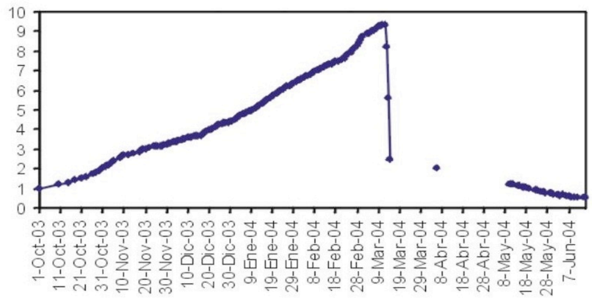

Fig. 3. Changes in water level of the lake BRS measured daily from 1 October 2003 to 26 June 2004.

The photograph of the glacier front area taken from the slope of Cerro Buenos Aires (Fig. 4) shows the ice-dam of about 300 m in width formed at the glacier front. Using Landsat TM image of 12 March 2001, an area of about 124 km^2 was derived for the BRS system; then it expanded to about 145.5 km^2 on 2 February 2004, reaching its maximum extent of about 154 km^2 on 11 March 2004, just prior to the ice-dam collapse. The total volume of water accumulated in the BRS system between 1 October 2003 and 11 March 2004 was estimated at around 1.0 km^3 (Skvarca and Naruse, 2006).

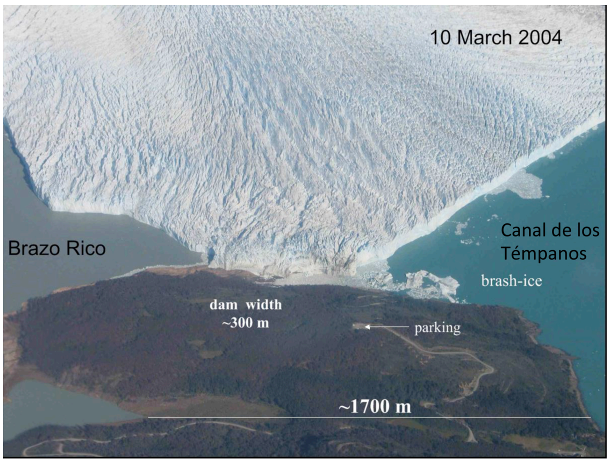

Fig. 4. The ice-dam at the front of Glaciar Perito Moreno, viewed from Cerro Buenos Aires on 10 March 2004.

3. Failure and Collapse of the Ice-dam in March 2004

On 11 March 2004, the water level of BRS reached the maximum, which was 9.9 m higher than CT. The mean ice thickness and the mean water depth in the frontal part of the glacier were estimated to be about 145 m and 100 m, respectively. Then the ice-dam was surely grounded, and the 'height above buoyancy', or 'ice thickness in excess of flotation' (Van der Veen, 1996), is calculated as 35 m.

From 11 March, the water level started gradual lowering, namely the water leakage through englacial and/or subglacial water veins turned to exceed the amount of the input water (due to glacier melting and precipitation) to BRS. Consequently, water flowing caused to enlarge the sizes of veins into water channels. Figure 5 exhibits the water level drop of BRS from 11 to 15 March, measured continuously with a water pressure gauge set on the southern coast of the lake.

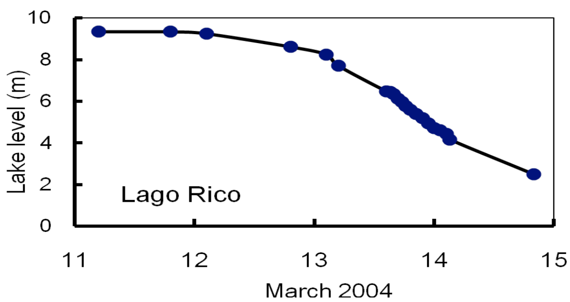

Fig. 5. Drop of water level of lake BRS during the ice-dam failure and collapse measured from 11 to 15 March 2004.

Water discharge Q is calculated from,

$$Q = - S(h)\, dh/dt + Q_{in}, \qquad (1)$$

where h is height of the water level of BRS, $S(h)$ is the surface area of BRS which is a function of h and varied from 154 km^2 on 11 March to 139 km^2 at 15:00 of 14 March, and Q_{in} is the water input to BRS that was estimated from the average rising rate of dh/dt when $Q = 0$ in Figure 3. Hydrograph of Q obtained during the failure and collapse of the ice-dam is shown in Figure 6. The peak Q of 8,400 m^3/s is found around the noon of 14 March.

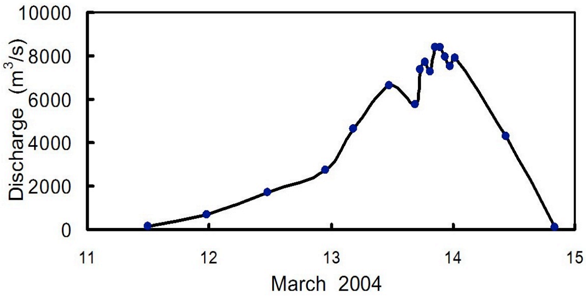

Fig. 6. Hydrograph of discharge Q during the outburst of the Perito Moreno ice-dam, calculated from Equation (1).

The crash of the tunnel about 30 m in diameter and collapse of the ice-dam of several tens of meters high almost instantaneously occurred on Sunday, 14 March 2004, at 19:09, with thunderous applause of hundreds of tourists who had been expecting something spectacular in the dim afternoon on the observation deck just in front of the glacier.

4. Numerical Estimation of the Development of Water Channel beneath the Ice-dam

To examine the development of water channel in the ice-dam, the following assumptions were made:

1) One cylindrical, straight channel of diameter d and 200 m in length exists near the glacier bed. Note that, though the apparent width of the ice-dam was about 300 m (Fig. 4), the effective water channel is considered as much shorter than it.
2) The 75% of the potential energy (ψ), which is originated from the height difference of the lake levels between BRS and CT, is converted to kinetic energy (ϕ) of the drained water, and the rest, 25% of ψ, is consumed to melt ice within the channel. Thus, for a unit mass of water,

   $\psi = g(h - h_0)$ and

   $$\phi = 0.75\psi = (1/2)\, v^2, \qquad (2)$$

   where h_0 is the water level at the outlet of the water channel in CT, g the acceleration of gravity, and v the average speed of water flow in the channel. The level difference $(h - h_0)$ varied from 9.9 m at 17:00 of 11 March to 5.9 m at 09:00 of 14 March.

3) The temperature of water flowing into the channel is 0.0°C. Although water temperature in the bottom layer at about 100 m apart from the glacier was +3 ~ 4°C (Fig. 7), the temperature of water just close to the ice body is considered about 0°C.

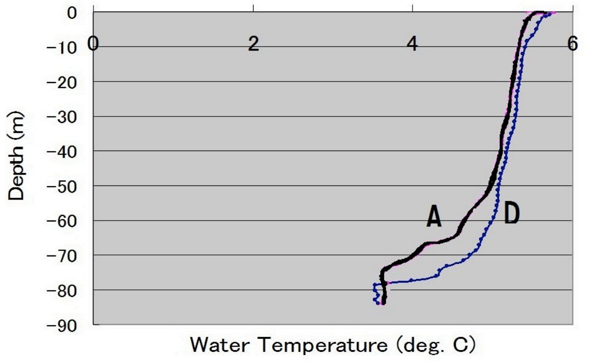

Fig. 7. Vertical profile of water temperatures in Brazo Rico, at about 100 m apart from the calving terminus of Glaciar Perito Moreno, measured on 16 December 2000. A thin line with dots (D) indicates the measurements during the descent of the senser, and a thick curved line (A) those during the ascent.

Applying an energy transfer model developed by Isenko (2005) and Isenko *et al*. (2005) to the converted energy of 0.25ψ, melting rates of ice in the channel, *i.e*. changes in diameter d, were calculated, as shown in Figure 8.

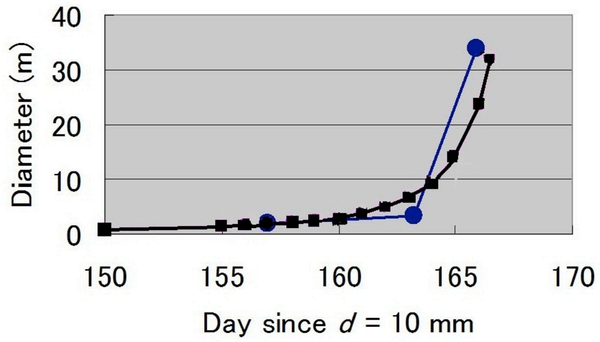

Fig. 8. Development of a water channel beneath the ice-dam of Glaciar Perito Moreno during about 17 days before the collapse. Small squares indicate channel diameters calculated from melting of ice with an energy transfer model in a water channel within a temperate glacier, and three large circles indicate those estimated from the discharge Q and water flow speed v using Equation (3).

The diameter d can also be derived by putting Q (calculated from Equation 1) and v (estimated from Equation 2) into

$$Q = \pi\,(d/2)^2\,v. \qquad (3)$$

The estimated diameters (three points) are also plotted together in Figure 8. Diameters derived by the two different methods coincide fairly well.

It can be read that it took five months (October 2003 - March 2004) for a vein to grow from 0.01 m to 1 m in diameter; 10 days for a channel from 1 m to 10 m in diameter; 2.5 days (12-14 March 2004) for a tunnel from 10 m to 30 m in diameter.

5. Comparison of Glacial Outbursts

In the event of the outburst from 11 to 15 March 2004, a total of 144 km^2 x 6.9 m = 0.99 km^3 of water was drained during three and a half days. This figure is in a good agreement with 0.97 km^3, the amount of water added to the volume of the main lake, LA, by the outburst, which was estimated from multiplying the area of LA (about 1,345 km^2) by the rise in the LA level (0.72 m).

For a comparison of various glacial outbursts, the hydrograph (Fig. 6) is replotted in Figure 9, along with those at Hubbard Glacier (Trabant *et al.,* 2003; Motyka and Truffer, 2007) and at Grimsvötn Ice Cap [reproduced from Paterson (1994)]. It is clearly recognized that the outburst due to the failure of the moraine-dam at Hubbard Glacier (2002) was very rapid and intense, by draining a total of 3 km^3 within 30 hours (Motyka and Truffer, 2007), and the outburst caused by jökulhlaup (release of water from the subglacial lake) of Grimsvötn Ice Cap (1954) exhibits a gradual, long-term discharge which lasted over 15 days. Behavior due to failure and collapse of the ice-dam at Glaciar Perito Moreno is an intermediate manner between these two.

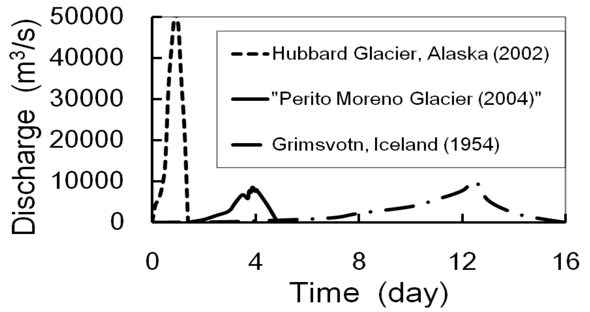

Fig. 9. Hydrographs of three kinds of glacial outbursts. Broken line: Moraine-dam failure of Hubbard Glacier (2002). Solid line: present study (Fig. 6). Broken & dotted line: Jökulhlaup of Grimsvötn Ice Cap (1954).

6. Summary and Conclusions

1) In September 2003, the front of Glaciar Perito Moreno reached the opposite bank, thereby blocking the water drain from Brazo Rico to Lago Argentino. The water level of Brazo Rico rose continuously until 11 March 2004, when the water reached the highest level at 9.35 m above the normal, being 9.9 m higher than the leeside of the dam, Canal de los Témpanos.

2) Due to dissipation of potential energy from flowing water within a subglacial or englacial water channel, melting of ice wall was accelerated with time. Numerical calculations showed that a vein of 0.01 m wide grows to 1 m in 5 months, a channel of 1 m wide grows to 10 m in 10 days, and a tunnel of 10 m wide to 30 m within 2.5 days.

3) In the outburst event caused by the failure and collapse of the ice-dam from 11 to 15 March 2004, a total of 0.99 km^3 water was drained in 3.5 days, which agreed well with the estimated total water gain of Lago Argentino (0.97 km^3).

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