Glaciological and Geomorphological Researches in Patagonia: 2003 – 2009 (ed. by M. Aniya and R. Naruse, 2012, pp. 175-179)

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

**Renji Naruse[1] and Pedro Skvarca[2]**

[1] Glacier and Cryospheric Environment Research Laboratory, 2-339 Higashi-machi, Tottori 680-0011, Japan
[2] Instituto Antártico Argentino, Cerrito 1248, C1010AAZ Buenos Aires, Argentina.

**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).

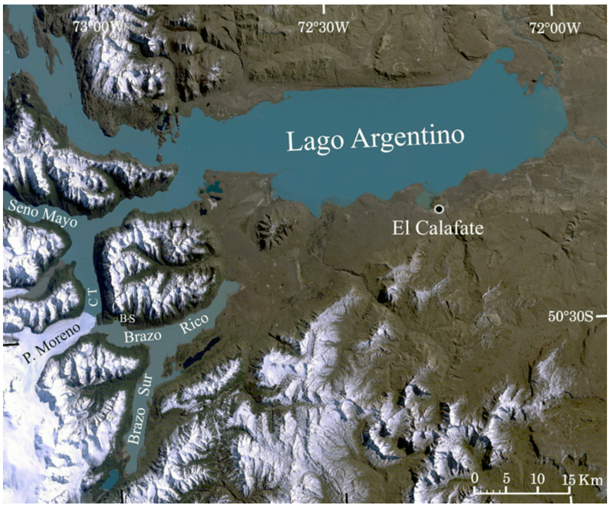


**Fig. 1. Landsat 5 image (Mar. 21, 2001) showing Glaciar Perito Moreno and the surrounding area. CT: Canal de los Témpanos. B-S: Bajo de las Sombras.**

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

## 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.

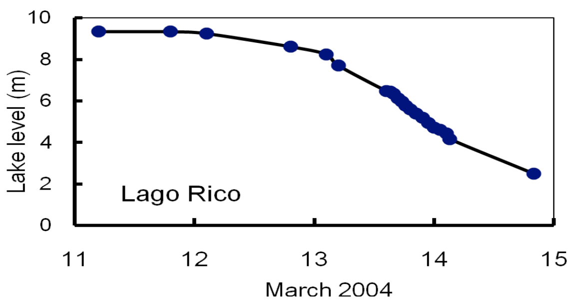


**Fig. 5. Drop of water level of lake BRS during the ice-dam failure and collapse measured from 11 to 15 March 2004.**

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.

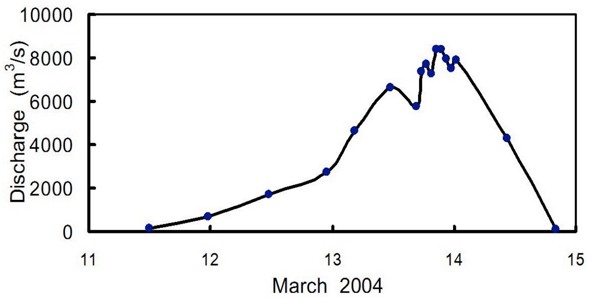


**Fig. 6. Hydrograph of discharge $Q$ during the outburst of the Perito Moreno ice-dam, calculated from Equation (1).**

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 ($\psi$), which is originated from the height difference of the lake levels between BRS and CT, is converted to kinetic energy ($\phi$) of the drained water, and the rest, 25% of $\psi$, is consumed to melt ice within the channel. Thus, for a unit mass of water,

$$\psi = g(h - h_0) \qquad \text{and}$$

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

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.

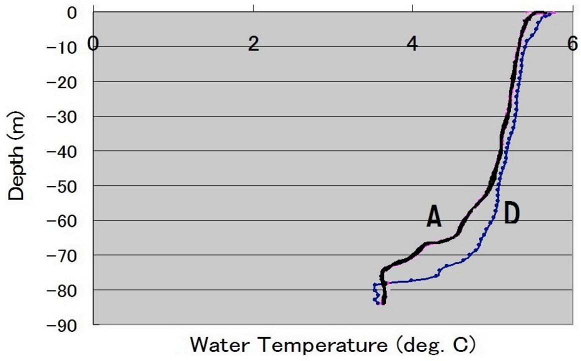


**Fig. 7. Vertical profile of water temperatures in Brazo Rico, at about 100 m apart from the calving terminus of Glaciar Perito Moreno, measured on 16 December 2000. A thin line with dots (D) indicates the measurements during the descent of the senser, and a thick curved line (A) those during the ascent.**

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

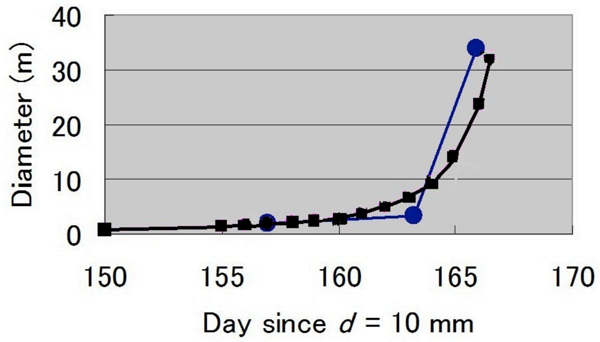


**Fig. 8. Development of a water channel beneath the ice-dam of Glaciar Perito Moreno during about 17 days before the collapse. Small squares indicate channel diameters calculated from melting of ice with an energy transfer model in a water channel within a temperate glacier, and three large circles 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.

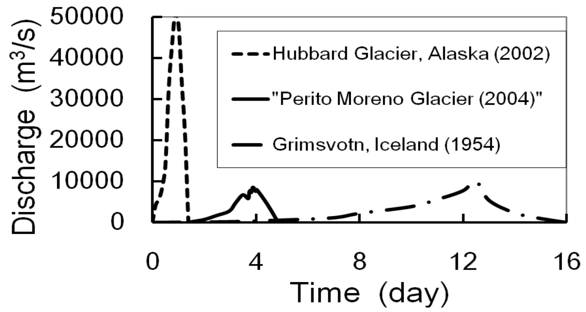


**Fig. 9. Hydrographs of three kinds of glacial outbursts. Broken line: Moraine-dam failure of Hubbard Glacier (2002). Solid line: present study (Fig. 6). Broken & dotted line: Jökulhlaup of Grimsvötn Ice Cap (1954).**

## 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 $km^3$).

**Acknowledgements:** This work is based on results of "Glaciological Research Project in Patagonia (GRPP)" from 1990 to 2004, funded by the Ministry of Education, Science, Sports and Culture of Japan, as well as a contribution to the project "Ice-climate Interaction and Dynamics of Glaciers on Antarctic Peninsula and Southern Patagonia" of Instituto Antártico Argentino-Dirección Nacional del Antártico. We are very thankful to Compañía Hielo y Aventura, Prefectura Naval Argentina, Parque Nacional Los Glaciares and all their staff for an efficient logistic support during many field campaigns carried out on Glaciar Perito Moreno from 1990 to 2004. We are also grateful to K. Satow and E. Isenko for collaboration in fieldwork during the summer of 2003/04, to O. Kloster, B. Roil and H. Svetaz for providing valuable information, and to M. Aniya for helpful comments to this report.

## References

Aniya, M., and Skvarca, P. (1992): Characteristics and variations of Upsala and Moreno glaciers, southern Patagonia. *Bulletin of Glacier Research*, **10**: 39-53.

Aniya, M., Sato, H., Naruse, R., Skvarca, P., and Casassa, G. (1997): Recent glacier variations in the Southern Patagonia Icefield, South America. *Arctic and Alpine Research*, **29** (1): 1-12.

Isenko, E. (2005): *Development and Evolution of Water Drainage Channels in Temperate and Polar Glaciers*. Unpublished Ph.D. Dissertation, Graduate School of Environmental Earth Science, Hokkaido University, Sapporo, Japan, 73p.

Isenko, E., Naruse, R., and Mavlyudov, B. (2005): Water temperature in englacial and supraglacial channels: change along the flow and contribution to ice melting on the channel wall. *Cold Regions Science and Technology*, **42**: 53-62.

Liss, V. C. C. (1970): Der Morenogletscher in der Patagonischen Kordillere: sein ungewohnliches verhalten seit 1899 und der eisdamm durchbruch des jahres 1966. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **VI** (1-2): 161-180.

Motyka, R.J., and Truffer, M. (2007): Hubbard Glacier, Alaska: 2002 closure and outburst of Russell Fjord and postflood conditions at Gilbert Point. *Journal of Geophysical Research*, **112**, F02004: 1-15.

Naruse, R., Aniya, M., Skvarca, P., and Casassa, G. (1995a): Recent variations of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments. *Annals of Glaciology*, **21**: 297-303.

Naruse, R., Skvarca, P., Satow, K., Takeuchi, Y., and Nishida, K. (1995b): Thickness change and short-term flow variation of Moreno Glacier, Patagonia. *Bulletin of Glacier Research*, **13**: 21-28.

Paterson, W. S. B. (1994): *The Physics of Glaciers*. 3rd Edition, Pergamon, Elsevier Science Ltd., Oxford, 480p.

Rott, H., Stuefer, M., Siegel, A., Skvarca, P., and Eckstaller, A. (1998): Mass fluxes and dynamics of Moreno Glacier, Southern Patagonia Icefield. *Geophysical Research Letter*, **25**: 1407-1410.

Skvarca, P., and Naruse, R. (1997): Dynamic behavior of Glaciar Perito Moreno, southern Patagonia. *Annals of Glaciology*, **24**: 268-271.

Skvarca, P., and Naruse, R. (2006): Overview of the ice-dam formation and collapse of Glaciar Perito Moreno, southern Patagonia in 2003/04. *Journal of Glaciology,* **52** (177): 318-320.

Skvarca, P., Naruse, R., and Angelis, H. (2004): Recent thickening trend of Glaciar Perito Moreno, southern Patagonia. *Bulletin of Glaciological Research*, **21**: 45-48.

Stuefer, M. (1999): *Investigations on Mass Balance and Dynamics of Moreno Glacier Based on Field Measurements and Satellite Imagery*. Unpublished PhD thesis, University of Innsbruck.

Stuefer, M., Rott, H., and Skvarca, P. (2007): Glaciar Perito Moreno, Patagonia: climate sensitivities and glacier characteristics preceding the 2003/04 and 2005/06 damming events. *Journal of Glaciology*, **53** (180): 3-16.

Trabant, D.C., March, R.S., and Thomas, D.S. (2003): Hubbard Glacier, Alaska: Growing and advancing in spite of global climate change and the 1986 and 2002 Russell Lake outburst floods. *USGS Fact Sheet* 001-03, 1-4.

Van der Veen, C. J. (1996): Tide-water calving. *Journal of Glaciology*, **42** (141): 375-385.