Activity report for ILTS Research Fund 2009

Hot water drilling at Glaciar Perito Moreno, Patagonia

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1. Introduction

Conditions beneath a glacier (e.g. subglacial water pressure, subglacial drainage system, unconsolidated sediment layer, bedrock roughness) are very important for glacier motion. These conditions control ice sliding over a bedrock and subglacial sediment deformation, causing substantial changes in glacier flow speed. The importance increases in the case of Glaciar Perito Moreno which terminates in lakes named Brazo Rico and Canal de los Témpanos (Figure 1a) (e.g. Aniya and Skvarca, 1992; Naruse et al., 1995; Skvarca and Naruse, 1997, Stuefer et al., 2007). The bed of this glacier is expected to be at high water pressure under the influence of the proglacial lakes. According to the seismic soundings performed by Stuefer et al. (2007), the glacier bed elevation is 150-400 m below the lake level within the reach of 10 km from the terminus (Figure 1b). A substantial part of ice overburden pressure is cancelled by the subglacial water pressure, which is a condition preferable for basal ice motion (e.g. Bindschadler, 1983).

In 2008/2009 austral summer season, we carried out high frequency ice flow measurements on Glaciar Perito Moreno and found clear diurnal flow speed variations (Sugiyama et al., 2009). The flow speed was closely correlated to the air temperature, which suggested that melt water production controlled the subglacial water pressure resulting in the changes in the basal ice motion. The flow speed was very sensitive to the melt water input, probably because the relationship between the water pressure and flow speed is highly nonlinear when the pressure rose up close to the overburden pressure (Bindschadler, 1983; Truffer and Iken, 1998; Sugiyama and Gudmundsson, 2004).

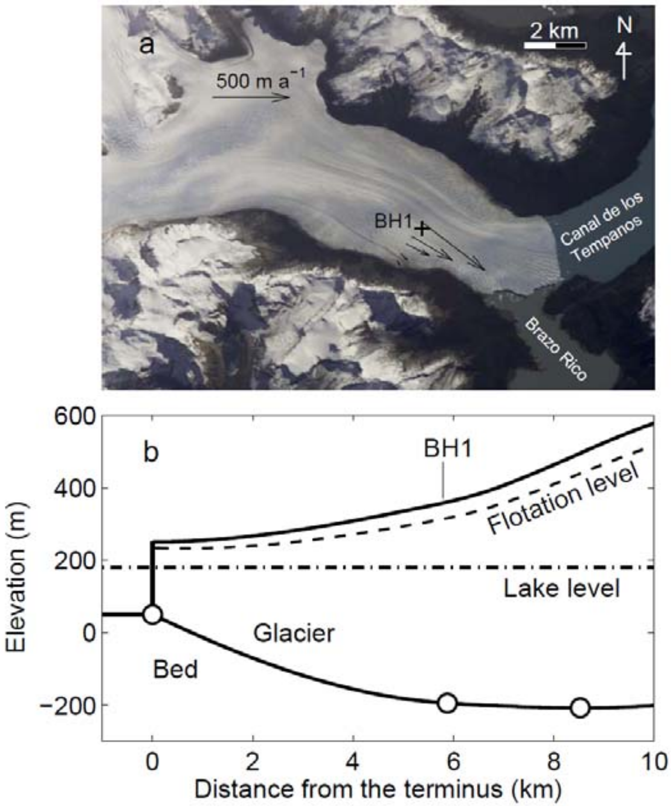

Figure 1. (a) Satellite image of Glaciar Perito Moreno. The drilling site is indicated by (+) and summer flow speeds measured from 31 December 2008 to 7 January 2009 are shown by the vectors. The image was taken on 27 March 2002 (image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center). (b) Longitudinal cross section of Glaciar Perito Moreno along the central flowline. The bed profile is drawn by interpolation of observational data points (○) (Stuefer et al., 2007). The lake water level and ice flotation level are indicated by the dot-dashed and dotted lines.

To test this hypothesis, we drilled Glaciar Perito Moreno with a hot water drilling system for subglacial water pressure measurements. This was the first attempt in Patagonia to drill through a glacier for subglacial observations. The aim of this report is to describe the hot water drilling system used for this project and details of the drilling operation carried out in 2010.

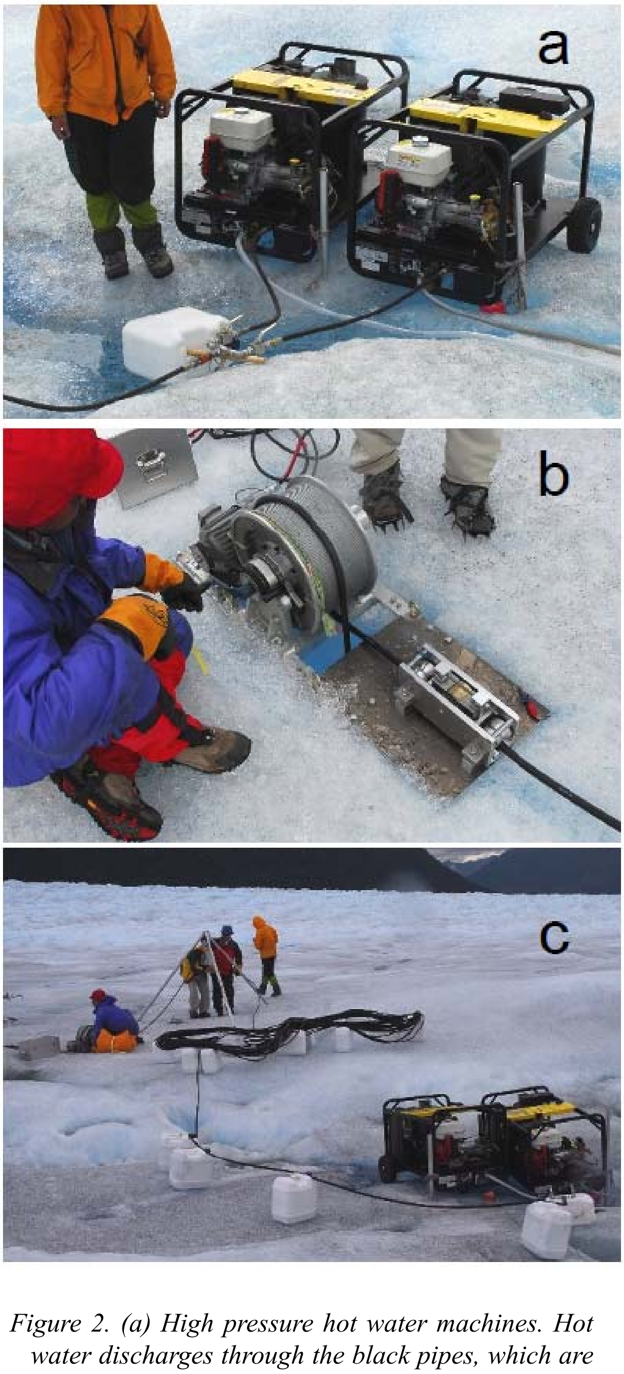

Figure 2. (a) High pressure hot water machines. Hot water discharges through the black pipes, which are combined into one hose with the piping. (b) Winch system with a brake in the lower right. (c) Hot water drilling system set up on Glaciar Perito Moreno. The borehole is at the middle left.

2. Hot Water Drilling System

The hot water drilling system was prepared by adapting an existing system owned by the Institute of Low Temperature Science, Hokkaido University (Sugiyama et al., 2008; Tsutaki and Sugiyama, 2009). The original system was designed for drilling up to 200 m thick ice, thus it was necessary to increase the capacity to drill through Glaciar Perito Moreno whose thickness was expected to be 450-550 m at our study site. We increased the number of high pressure hot water machines (Kärcher HDS1000BE) and constructed piping to bring hot water from the machines together (Figure 2a). The length of drilling hose was extended to 550 m. An electricity powered winch system (Figure 2b) was developed to lower down and lift up the hose in a borehole, as it becomes too heavy to handle by man power during deep drilling. At Glaciar Perito Moreno, we controlled the winch by hand without electricity using a handle connected to a gear system as observed in Figure 2b. Electric power from a generator was used only to wind up the hose after the drilling was completed. The winch was equipped with a brake system (lower right in Figure 2b) designed and constructed in a workshop of the Institute of Low Temperature Science. This brake keeps the hose tightly wound around the winch drum, so that necessary friction was generated at the interface between the hose and the drum.

The hot water machines draw water with petrol driven pumps from a water basin or supraglacial water source. The water is warmed up with a heater which uses diesel as fuel. Hot water flows through 1/2 inch diameter high pressure hoses (Bridgestone WAR08) before it emits a narrow water jet from a 3.5 mm diameter nozzle (Katorigumi Inc. K-18). The nozzle is mounted on a 3-m long metal pipe, which provides a load to straighten the hose for drilling a vertical borehole. For drilling shallow boreholes, a tripod and pulley system was used instead of the winch. The weight of all the drilling equipment is approximately 600 kg exclusive of fuel.

The drilling system was tested in Sapporo before the field campaign. The system generates hot water of about 70°C at a rate of 1600 l hr^{-1} and a pressure of 10 MPa. The water temperature and the flow rate show that the new system generates approximately two times greater amount of heat as compared to the original system.

3. Overview of Field Campaign

The field campaign began on 24 February 2010. The location of the drilling site was determined to fulfill the conditions such as, availability of water, flat surface for drilling and helicopter operations, proximity to 2008/09 GPS measurement sites, and ice thickness not greater than hose length. After a reconnaissance visit on 24

February, the drilling site was chosen at S50° 29' 27.2", W73° 5' 39.5" (Figure 1a). The site was 5.8 km from the terminus and about 300 m off the central flowline. The ice thickness was estimated as 450-550 m from the seismic data (Stuefer et al., 2007). Water was available in a nearby supraglacial pond. Drilling equipment and fuel (400 l of diesel for the heaters and 150 l of petrol for the pumps and generator) were transported on 25 February by a helicopter of Gendarmería Nacional from Puerto Bajo De Las Sombras about 7.5 km southeast of the drilling site. We set up the system immediately after the transportation and began the drilling on 26 February. As the drilling site was two hours walk from our camp, our activity on the glacier was limited from 1000 to 1900 hrs. The drilling was continued until March 5 and equipment was evacuated from the glacier on the next day.

4. Hot Water Drilling

The drilling did not progress efficiently until 28 February because one of the pumps needed to be repaired and the winch system had to be tested. The first borehole (BH1) reached the glacier bed on 2 March after the consumption of 235 l of diesel and 90 l of petrol. Total time of the hot water system operation was 21 hours, including time spent for testing the devices. Fuel consumption rates in total were 11.2 l h^{-1} for the diesel and 4.3 l h^{-1} for the petrol. The diesel consumption rate was smaller than usual because we used only one of the two hot water machines for the upper part of the borehole. The second borehole (BH2) was drilled approximately 5 m downglacier from BH1. We started the drilling on 4 March and completed on the next day after 10.5 hours of operation. The diesel and petrol consumption rates were 15.7 and 3.9 l h^{-1}, respectively.

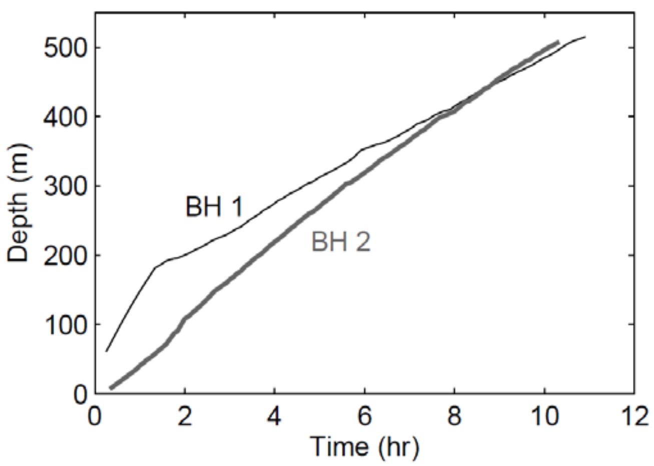

Figure 3. Depth of the boreholes v.s. drilling duration for the drilling of BH1 (black) and BH2 (bold gray).

Figure 3 shows the depth of the boreholes as a function of the drilling duration. The drilling rate was not uniform for BH1 as we drilled by hand with the tripod and pulley system for the first 193 m. The winch system was used for the deeper part of BH1 and for the entire part of BH2. Drilling rates from the surface to the depth of 510 m were 48 and 50 m h^{-1} for BH1 and BH2, respectively.

In order to detect the glacier bed during drilling, we measured the weight of the drilling hose hanging in the borehole every 5 to 20 m. A rope was twisted around the hose to hang it under a hook of a spring scale. Clear changes in the load were observed at 340 m in BH1 and 369 m in BH2. These sudden increases were attributed to the drainage of the water in the borehole as described later in this section. At the hose length between 505-511 m, the load suddenly dropped in both of the two boreholes and decreased progressively as we continued the drilling (Figure 4). Detailed measurements in BH1 showed that the change could be reproduced by lowering and lifting the hose at this depth (Figure 4 inset). These were clear indications that the drilling nozzle hit the bed. The load decreased because the hose came into contact with the bed and the borehole wall. Because of these observations, we conclude that the ice thickness at the drilling site was 505-511 m plus several meters stretching of the hose. This result agrees with the seismic data (Stuefer et al., 2007).

Boreholes are usually filled with water during hot water drilling. The water often drains when the borehole reaches the bed, but the drainage occurs also within the glacier. These events provide important information on

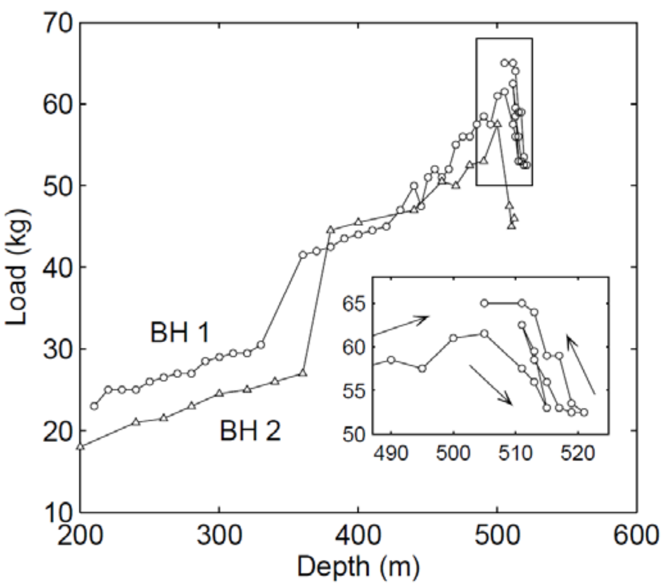

Figure 4. Weight of the drilling hose measured during the drilling of BH1 (○) and BH2 (Δ). The inset shows details near the bed in BH1.

subglacial and englacial hydrological connections. Water in BH1 first drained at 172 m. The sudden reduction in the hose weight at 340 m (Figure 4) implies the water drained again and buoyancy force acting on the hose decreased. In BH2, the drainage occurred at 369 m which is indicated by the change in weight (Figure 4). According to our visual observation of the water level in the boreholes, the rate of drainage was in a range of 10^{-2}–10^{-1} m^3 min^{-1}, which was relatively smaller than those we experienced in other glaciers in the Alps. These observations suggest the existence of englacial drainage system in Glaciar Perito Moreno.

The inspection of a hot water jet nozzle after the drilling provided a clue to the glacier bed condition. Surface of the brass made nozzle is often heavily scratched or scraped when it hit bedrock. However, the nozzle used for BH1 had only a small scratch mark and that for BH2 had no indication of contact to rocks. Therefore, it is likely that the glacier is underlain by a soft sediment layer at the drilling site.

After the drilling was completed, water pressure sensors (Geokon 4500S and HOBO U20) were installed in the two boreholes to measure the borehole water level. The measurements showed that water levels in BH1 and BH2 correlated very well. They fluctuated in a diurnal manner within a level between 430-460 m from the bed, which corresponded to more than 90% of the ice flotation level in the region. The pressure variations were correlated to surface flow speed and air temperature, suggesting our hypothesis was correct. Further analyses of the water level variations together with ice flow speed and air temperature data are in progress.

5. CONCLUSION

We drilled through Glaciar Perito Moreno to the bed using a hot water system. Two boreholes were drilled to carry out first subglacial measurements in Patagonia. The drilling confirmed that ice thickness at the drilling site was in a range of 505-511 m. The completion of drilling through to the bed was clearly detected by the change in weight of the drilling hose hanging in boreholes. Water in the boreholes drained before the drilling reached the bed, indicating the existence of englacial drainage systems. The glacier is probably underlain by a soft sediment layer according to inspection of hot water nozzles after the drilling. Water level in the boreholes after the drilling was at more than 90% of ice flotation level, which strongly suggests the ice flow regime of Glaciar Perito Moreno is primarily controlled by the subglacial water pressure and its variations.

In order to drill the glacier to the depth more than 500 m, two high pressure hot water machines were assembled with a newly constructed winch system. The rate of drilling from the surface to bed was 50 m h^{-1} when the system was running properly. Fuel consumption rates were 15.7 l hr^{-1} for diesel and 3.9 l hr^{-1} for petrol.

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