Name of research institute or organization:

Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zürich

Title of project:

Jökulhlaups from Gornersee

Project leader and team:

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Project description:

In the following report we give a short overview of our work done on Gornergletscher since 2004 (Huss et al., 2007, Sugiyama et al., 2007 and Sugiyama et al., submitted).

Since 1970 we identified significant drainage events every year except for 1984, 1991 and 1995. Fig. 1a presents the evolution of the lake outburst timing showing an obvious trend.

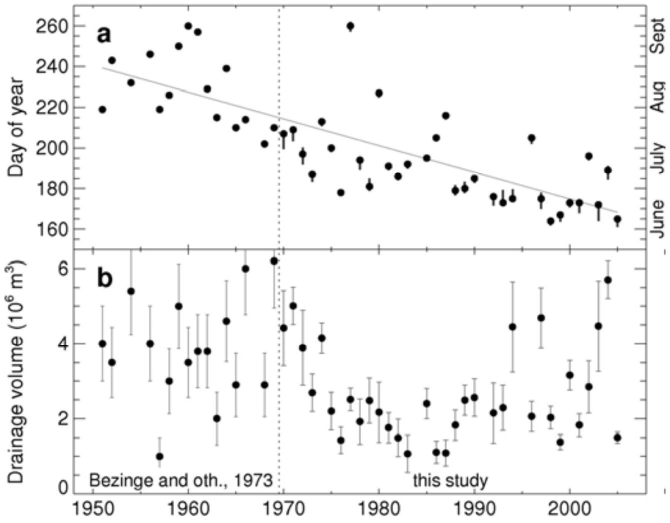

Figure 1: (a) Evolution of lake outburst timing. The dots correspond to the date of the peak discharge. In 1984, 1991 and 1995 no drainage events could be found. Vertical bars (after 1970) show the duration of the drainage events. (b) Evolution of drainage volume. Error bars indicate the uncertainty range of the calculated values.

Between 1950 and 2005 a shift of about two months has been observed, moving the expected date of the event from late August to late June. In contrast, the temporal evolution of drainage volume does not show an uniform trend. In addition to the year-to-year variability, long-term fluctuations of drainage volumes also occurred (Fig. 1b). Since only very limited direct observations exist, we do not know to what extent the volume fluctuations are caused either by changing the lake basin geometry or different filling levels of the lake.

Seismic investigations were performed for locating and characterizing the sources of deep ice-quakes and understanding their role in the lake drainage process. During the summers 2004-2006 up to 24 seismometers were installed on the glacier ice (Fig. 2).

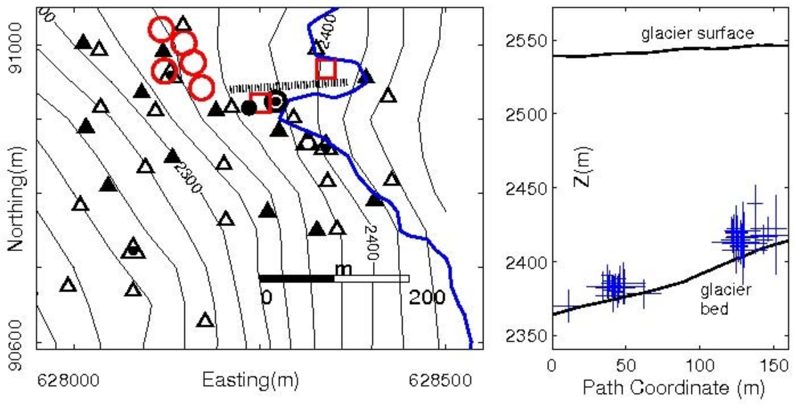

Figure 2: (left) Seismic arrays and epicenters of deep ice-quake clusters detected in 2004 (red empty squares) and 2006 (red empty circles). Empty and solid triangles represent the 2004 and 2006 seismic stations, respectively.
Additional deep borehole seismometers were installed at locations where dotted triangles are drawn. The blue solid line shows the 2004 lake outline. The black dot indicates the position of a borehole to the glacier bed equipped with a pressure sensor. The moulin into which the lake drained in 2006 is indicated by the circled dot. The contour lines correspond to the bed topography as determined by radio-echo sounding. The dotted line indicates the vertical cross-section path to show the hypocentral locations of the two 2004 ice-quake clusters (on the right of this figure). (Right): Hypocenters of the two 2004 clusters. The two black lines show the glacier surface and glacier bed. The crosses indicate the ice-quake locations and uncertainties thereof as determined by the arrival time inversion described in the text.

The analysis focused on three major aspects: Locations, source times and signal forms of the seismic signals.

- **Locations:** Most deep ice-quakes occurred near the glacier bed, some were located at intermediate depths. The large majority of basal ice-quakes tend to cluster at distinct locations (Fig. 2). Two and five main basal clusters were found in the years 2004 and 2006, respectively.
- **Source times:** The overall seismic activity increases during the warmest hours of the day. This is a result of melt water enhanced sliding yielding large deformation rates. The deep cluster ice-quakes, however, tend to occur in the early morning hours. Furthermore, no deep cluster ice-quakes were detected in the days following the initiations of the 2004 and 2006 lake drainages. Comparing these observations with the time series measured by pressure sensors in boreholes indicates that this type of ice-quakes preferentially occurs at low basal water pressures (Fig. 3).

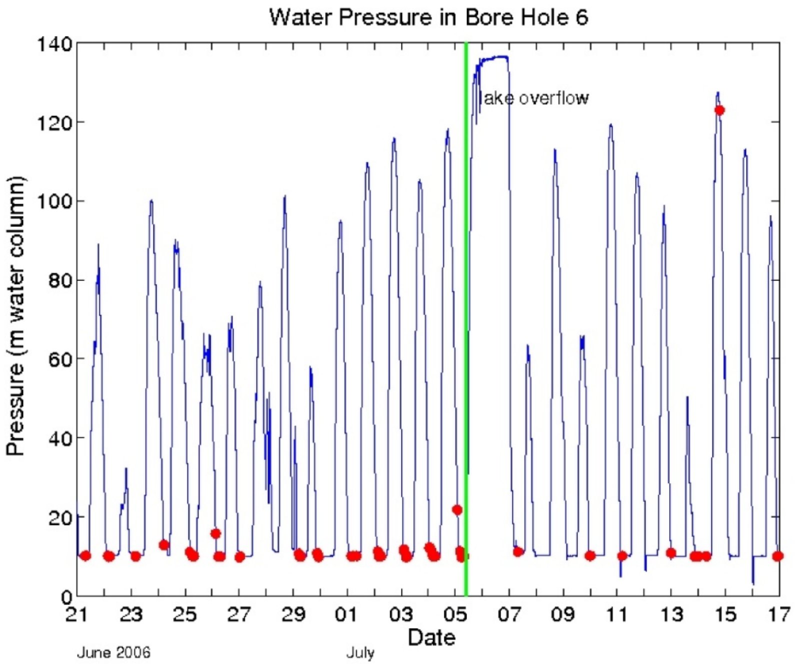

Figure 3: Basal water pressure as measured in the borehole close to the moulin into which the lake drained in 2006 (see Fig. 2). There is a low-pressure cutoff because the pressure sensor was located about 10 m above the bedrock.

The pressure shows large diurnal fluctuations as a consequence of good connection to the sub-glacial drainage system. Immediately after lake overflow, the moulin was saturated resulting in high water pressures even during the night. Once the drainage system had adjusted to the large amount of lake-water input the pressure is again prone to large diurnal fluctuations. The source times of the ice-quakes of the nearby basal clusters are indicated by the red dots. The seismic activity seems almost exclusively limited to times of low basal water pressures, with no deep ice-quakes occurring during the time of the moulin saturation.

- **Signal forms:** Seismic signals contain information about the source. In particular, the first arrivals of almost all deep cluster ice-quakes are exclusively compressive favouring tensile fracturing as a possible source. In order to rigorously characterize the source, numeric calculations of the seismic moment tensor are necessary.

These observations permit the following interpretation: The deep cluster ice-quakes appear to be due to large deformation rates of the basal ice layer. At falling water pressures, when sliding is inhibited, such large deformation rates may occur.

During the outburst event in July 2004, the ice surface moved vertically upward by up to 10 cm within a distance of 400 m from the lake. This suggests a separation of the glacier sole from the bed due to the intrusion of lake water. The largest surface upward motion was found in the zone where the ice floatation level was exceeded. This indicates that the seal broke as soon as the hydraulic potential line surpassed the level of the glacier bed. In addition to the afore-mentioned vertical displacement, the glacier surface was lifted up by 0.5-3 m within 100 m from the lake border. Moreover, the formation of a substantial englacial drainage could be observed in a borehole. This can be explained by an upward bend of the ice dam due to the buoyancy force, as illustrated in Fig. 4.

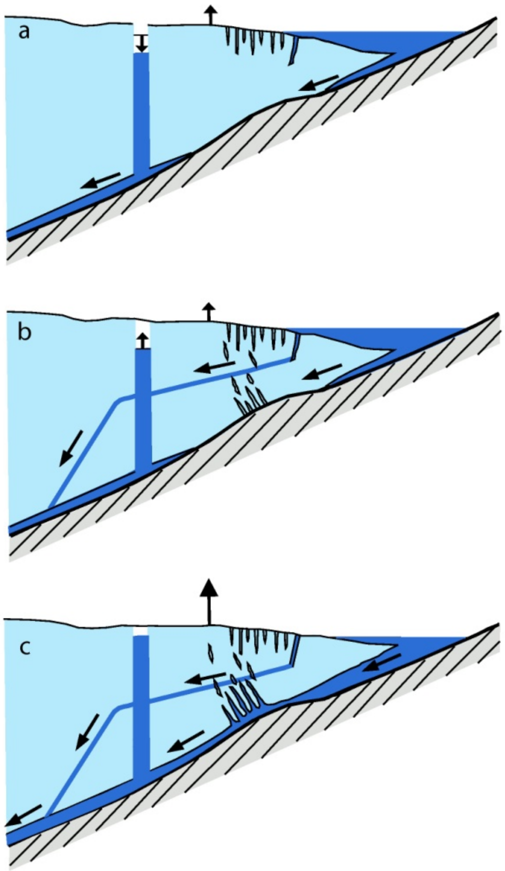

Figure 4: Schematic presentation of a possible triggering of the lake outburst. Due to the buoyancy force, the ice dam experienced a vertical displacement of up to 3 m. This caused the formation of englacial cracks with subsequent englacial drainage. Presumably, this englacial water flow triggered the sub-glacial drainage.

The englacial fracturing caused by the large upward displacement probably favored the initiation of the observed englacial lake water drainage. It is likely that the lake outburst was initiated by this englacial drainage, after which the sub-glacial water flow started in the basal opening caused by the upward bend of the marginal ice (Sugiyama et al., submitted).

References

Huss M., Bauder A., Werder M., Funk M. and Hock R. (2007), Glacier-dammed lake outburst events of Gornersee, Switzerland, Journal of Glaciology, 53 (181), p. 189-200.

Sugiyama S., Bauder A. Weiss P. Funk M. (2007), Reversal ice motion during the outburst of a glacier-dammed lake on Gornergletscher, Switzerland, Journal of Glaciology, 53 (181), p. 172-180.

Sugiyama S., Bauder A., Huss M. and Funk M. (submitted), Triggering and drainage mechanisms of glacier-dammed lake outburst in Gornergletscher, Switzerland, Journal of Geophysical Research.

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