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On the outburst of glacier-dammed lakes: Gornergletscher, Valais

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Introduction

The release of water from glaciers in catastrophic floods poses an important threat to human activity. Such events are called *jökulhlaups*, an expression from Iceland, where spectacular outburst events originate in large water bodies impounded within ice caps. In the Alps or in glacierized mountain areas in general, glacier-dammed lakes develop in a depression resulting from a combination of topographical conditions and glacier extent.

The most famous historical cases in the Swiss Alps, where such glacier-dammed lakes suddenly drained with disastrous consequences, are Glacier du Giétro, Allalngletscher, Grubengletscher and Aletschgletscher/Märjelensee. These outbursts represent a severe threat in mountain ranges and have caused major damage and loss of life in the past.

Lakes impounded behind an ice barrier drain in a variety of ways. Among the most well known are lake outbursts associated with a catastrophic drainage due to rapid thermal enlargement of subsurface chan-

nels. But sometimes, for unknown reasons, other mechanisms occur, even at the same location, owing to the complex nature of these events. The initiation of an outburst may be of particular complexity.

Jökulhlaups

Outburst floods from sub-glacial or ice-dammed lakes (e.g. Björnsson 1992) are commonly described to occur when the lake level has reached a critical level at which the hydrostatic water pressure maintained by the lake is equal to the ice overburden pressure of the ice dam (Fig. 1).

As soon as the line $\phi = 0$ in Fig. 1 just touches the bed curve, the seal breaks and the conditions for a sub-glacial outburst are met. As water begins to leak underneath the dam, flow typically localizes in one or a few channels forming in the ice. Such channels increase rapidly in size due to melt-back of the ice walls caused by the dissipation of potential energy (e.g. Röthlisberger 1972, Nye 1976). As lake drainage proceeds, water pressure in the channel drops and creep-closure of ice counteracts melt-enlargement progressively. The rapid closure or even collapse of the channel can stop the flood, even if the lake is not empty. The discharge of a typical *jökulhlaup*-hydrograph increases as a power law of time with a finite time singularity (because of progressive channel-

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growth) and a steep falling limb, reflecting rapid closure of the conduit (e.g. Rist 1955, Björnsson 1974) (Fig. 2).

Results for Gornergletscher

Gornergletscher is the second largest glacier in the Alps (Fig. 3). It consists of several tributaries and covers an area of nearly 60 km². At the confluence of Gorner- and Grenz-gletscher, Gornersee (an ice-marginal lake) has formed every spring and drained every summer for many years. In the last century Gornergletscher experienced a significant ice loss, especially in the lake area (150 m thinning since 1931, Fig. 4). The greatest ice thickness of Gornergletscher is 450 m at the confluence area (Huss et al. 2007) and the main glacial valley is slightly over-deepened. Significant changes of glacier geometry during the last century caused changes in lake location and volume (Fig. 4a). The lake usually starts to fill in May and drains annually between June and August (Bezinge et al. 1973). Often, the lake is filled to the maximum level beyond which supraglacial out-

flow would occur at the start of the drainage.

A gauging station operated by the Grande Dixence hydropower company is situated 1 km downstream of the glacier terminus, recording hourly discharge since 1970, providing the unique possibility to carry out an assessment of glacier floods. An evaluation of these data has shown that each year 1 to 6 Million m³ of meltwater are impounded by the lake and drains subglacially within a few days. The peak discharges during the outburst events, measured at the glacier terminus, reaches 20 to 50 m³ s⁻¹, of which 40-75% is lake water. In the first half of the 20th century flood intensities of more than 100 m³ s⁻¹ were reported, regularly causing severe damage in the valley of Zermatt (Raymond et al. 2003).

Since 1970 we identified significant drainage events every year except for 1984, 1991 and 1995. Fig. 5a presents the evolution of the lake outburst timing showing an obvious trend. 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. 5b). 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.

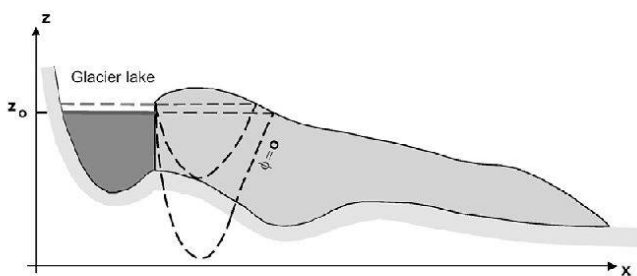


Fig. 1: Hydraulic potential lines $\phi = 0$ for two different lake levels z_0 .

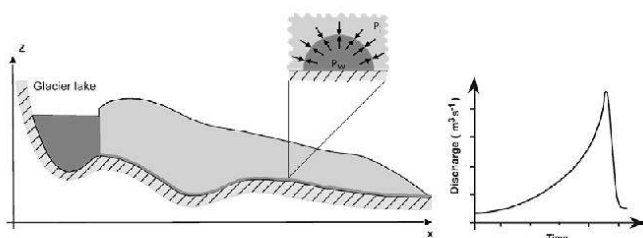


Fig. 2: Glacier dammed lake (left) and typical drainage hydrograph.

Triggering mechanism of the lake drainage

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

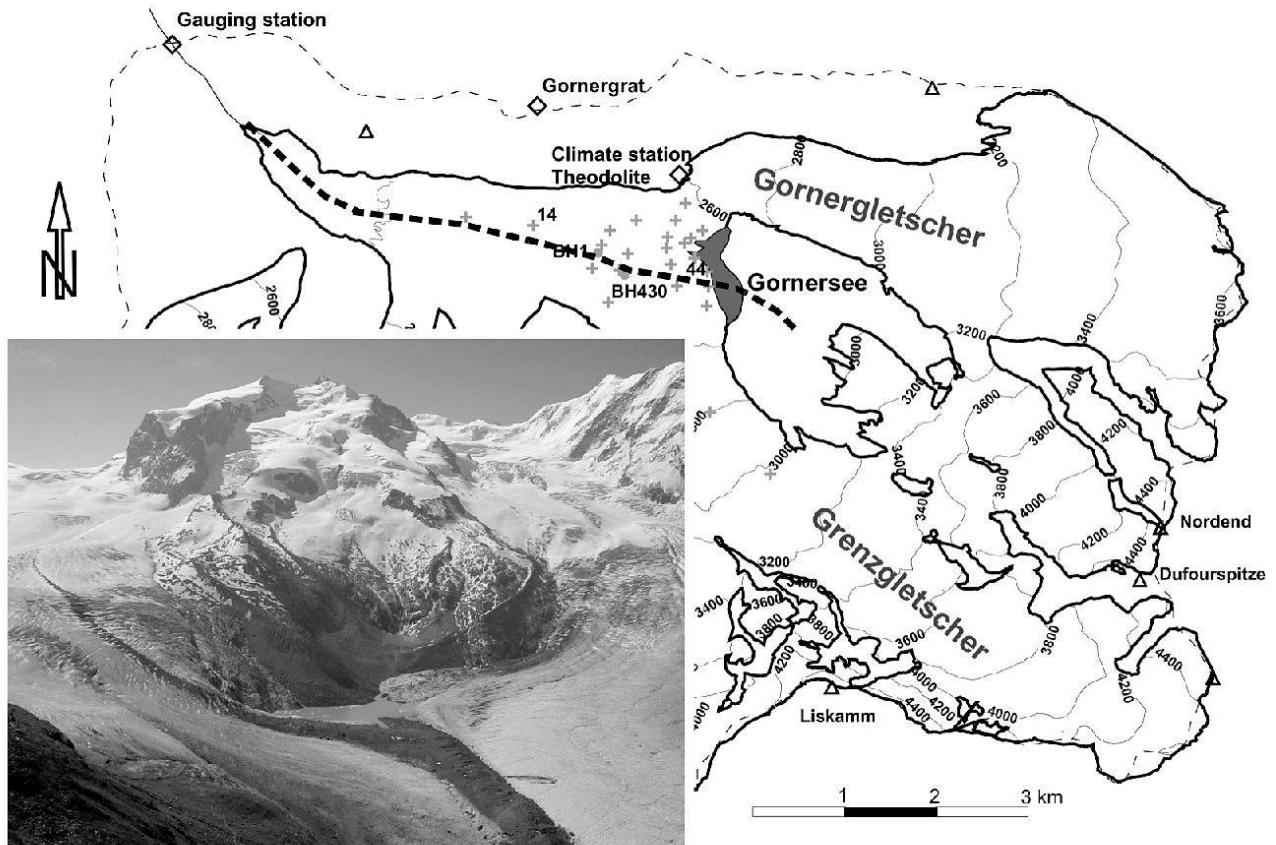


Fig. 3: Map of Gornergletscher. The central flowline used for the profiles in Fig. 4 is depicted by a dashed line. Photograph taken in July 2006 showing Gornergletscher and its two tributaries Grenz- and Gornergletscher (right and left) and Gornersee (at the confluence).

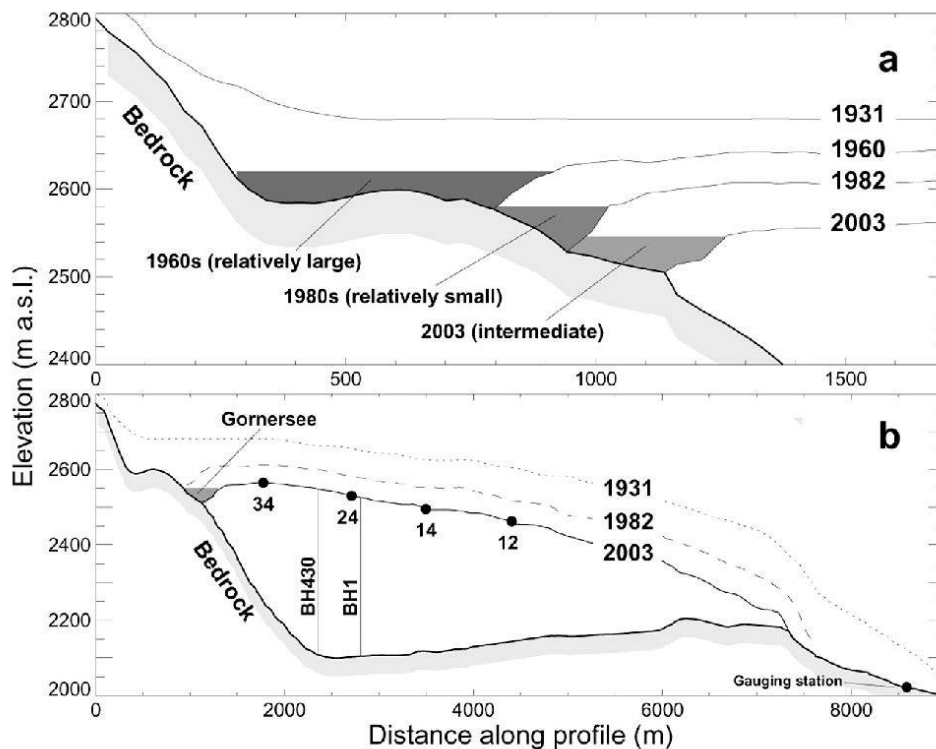


Fig. 4: (a) Schematic profile of the evolution of Gornersee in the last decades. The glacier surface of 1931 is based on a digitized map of the Swiss topographic survey, 1960 on an unpublished map by Wilhelm (1967), 1982 and 2003 on evaluated aerial photographs [Bauder et al. 2007]. (b) Longitudinal profile of the tongue of Gornergletscher. Bed topography is obtained from radio-echo soundings. Two boreholes and four stake locations are indicated [after Huss et al. 2007].

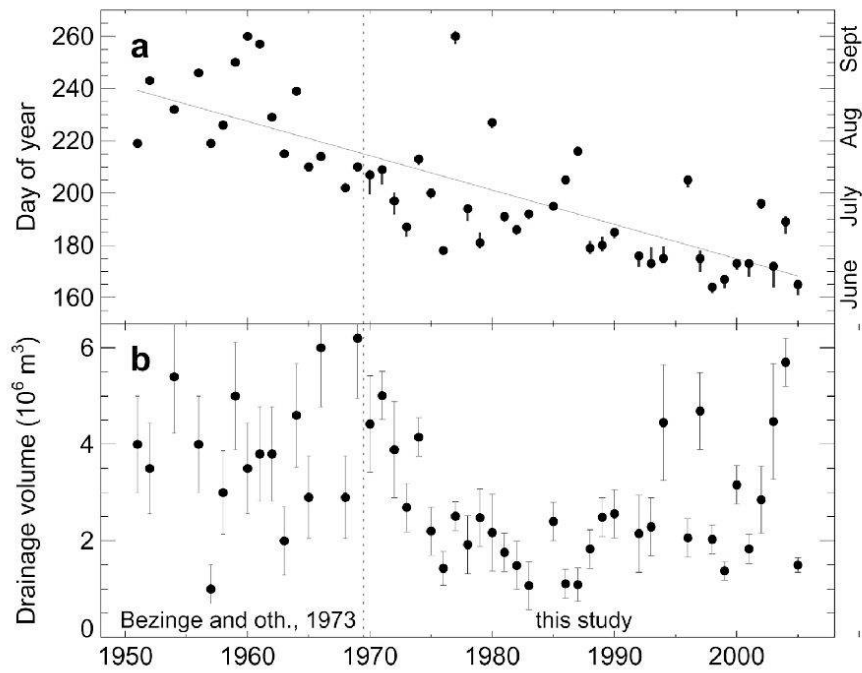


Fig. 5:
 (a) Evolution of lake outburst timing. The dots correspond to the date of the peak discharge. In 1984, 1991 and 1995 no drainage events could be found. Vertical bars (after 1970) show the duration of the drainage events. (b) Evolution of drainage volume. Error bars indicate the uncertainty range of the calculated values (after Huss et al. 2007).

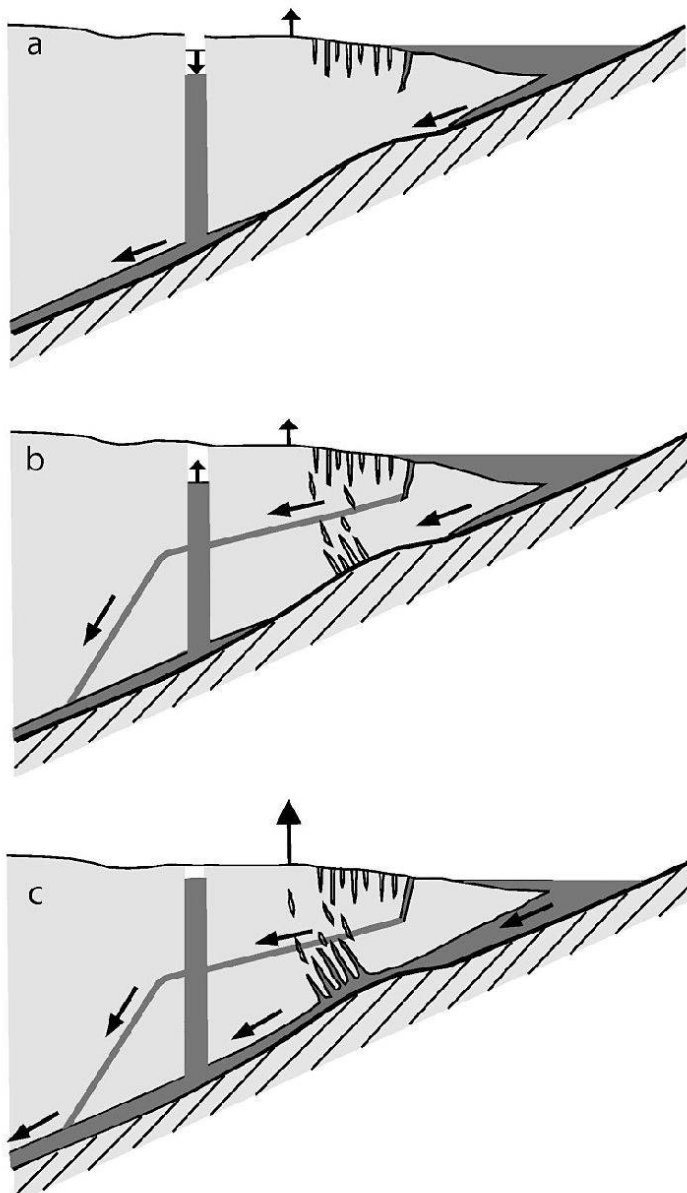


Fig. 6:
 Schematic presentation of a possible triggering of the lake outburst. Due to the buoyancy force, the ice dam experienced a vertical displacement of up to 3 m. This caused the formation of englacial cracks with subsequent englacial drainage. Presumably, this englacial water flow triggered the sub-glacial drainage (after Sugiyama et al. 2008).

floatation level was exceeded. This indicates that the seal broke as soon as the hydraulic potential line $\phi = 0$ surpassed the level of the glacier bed (Fig. 1). In addition to the aforementioned 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. 6. The englacial fracturing caused by the large upward displacement probably favoured 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. 2008).

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