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Triggering and drainage mechanisms of the 2004 glacier-dammed lake outburst in Gornergletscher, Switzerland

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[1] To investigate the triggering and the drainage mechanisms of a glacier-dammed lake outburst, we conducted high-frequency measurements of the ice surface motion in the vicinity of Gornersee, an ice marginal lake on Gornergletscher, Switzerland. During the outburst event in July 2004, the ice surface within a distance of 400 m from the lakeshore moved vertically upward by up to 0.1 m. This vertical surface motion cannot be explained by vertical straining of ice which was measured in one of the boreholes; therefore, we suggest the separation of the glacier sole from the bed was caused by subglacially drained lake water. Our observation indicates that the lake water drained as a sheet-like flow through the space created by the basal separation. The upward surface motion was greater in the region where the ice flotation level was exceeded by the lake level, implying that the ice barrier was breached when the lake water hydraulically connected to the bed and lifted up the glacier. In addition to the centimeter-scale vertical ice motion, three survey stakes located within 100 m from the lake showed extraordinarily large vertical displacement of 0.5–3.0 m associated with abrupt changes in horizontal flow direction. A plausible interpretation is that the marginal ice wedge bent upward because of the buoyancy force generated by the drained water. Such bending is possible if subglacial and englacial fractures formed at about 200 m from the glacier margin and acted as a hinge. The newly formed and preexisting englacial fractures probably took the role of inducing englacial water drainage which preceded the outburst.

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1. Introduction

[2] The outburst of a glacier-dammed lake is a sudden release of meltwater impounded in ice marginal, subglacial, englacial, or supraglacial locations [*Roberts*, 2005]. It can have substantial impact on the physical environment and can pose a serious hazard as it is difficult to predict the timing and magnitude of floods [e.g., *Haeberli*, 1983; *Björnsson*, 1992; *Richardson and Reynolds*, 2000; *Raymond et al.*, 2003]. Since a number of glacier-dammed lakes have been newly formed as a result of recent glacier retreats, it is urgently necessary to acquire a better understanding of the triggering and drainage mechanisms of lake outbursts.

[3] In general, glacier-dammed lakes start to drain when the lake level reaches a critical threshold, which varies depending on the triggering mechanism of the outburst [*Tweed and Russell*, 1999]. *Thorarinsson* [1953] proposed that the flotation of the ’ice dam’ (glacier adjacent to the lake) caused by the pressure of the lake water initiates the drainage. In this case, the outburst is expected to occur when the lake level exceeds the flotation level of the ice barrier and the lake water breaks through the seal underneath. Although some observations suggested flotation as the triggering mechanism [*Sturm and Benson*, 1985; *Knight and Russell*, 1993], many other outburst events were initiated before the flotation condition was met. The outburst of Grímsvötn, a subglacial lake in Iceland, usually occurs at the lake level which is 20–50 m less than that required for flotation [*Björnsson*, 1992, 2002]. *Nye* [1976] ascribed this discrepancy to the flexure of the ice floating on the subglacial lake, the so-called buoyant cantilever effect. Buoyant force acting on the floating part of the glacier pries the grounded ice off its bed, resulting in the flotation of the ice barrier at a subglacial pressure slightly less than the ice overburden pressure. Since the stress condition of the ice dam is influenced by the stress coupling with neighboring ice, the lake level required to breach the seal is not a simple function of the ice thickness at the point where hydraulic potential barrier exists. In addition to the lake level, the timing of the outburst is controlled by ice motion and crevasse formation, as well as certain character-

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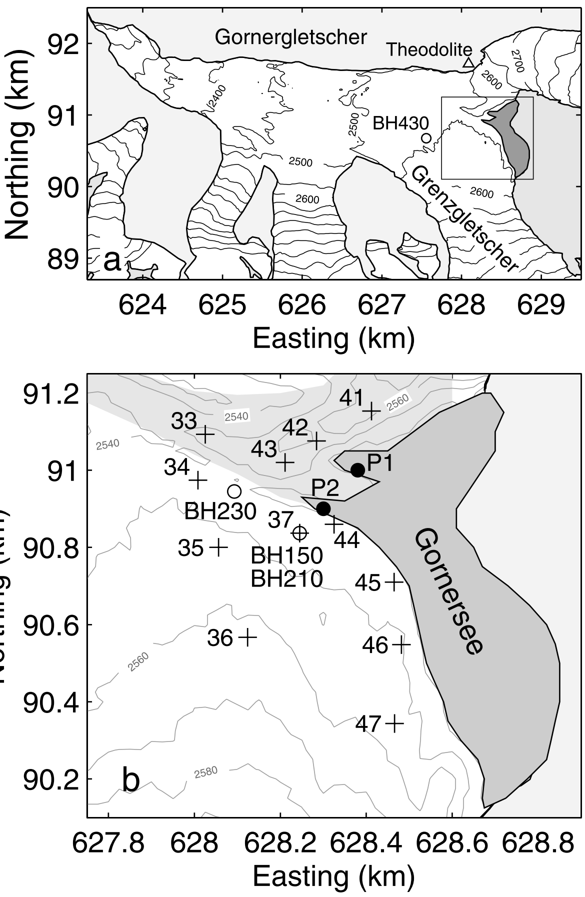

Figure 1. (a) Map of Gornergletscher and Grenzgletscher with the borehole (circle) and theodolite (triangle) locations and surface contour lines at intervals of 50 m. The study site is indicated by the box. (b) Locations of the survey stakes (crosses), boreholes (open circles), and englacial water channels (solid circles) with surface contour lines at intervals of 10 m. The boreholes BH210 and BH150 are in the same location. The shading on the glacier shows the medial moraine.

istics of the ice dam, e.g., hydraulic connection at the bed, the possible existence of a subglacial sediment layer [*Fowler and Ng*, 1996], and debris content of the ice [*Tweed*, 2000]. For this reason it is very difficult to predict lake outburst timing.

[4] The water drainage through a glacier during a lake outburst has been studied in a theoretical way by many authors, who relied on the assumption that the lake water drains through a single conduit [*Nye*, 1976; *Spring and Hutter*, 1981, 1982; *Clarke*, 1982, 2003; *Fowler*, 1999]. These theoretical investigations successfully reproduced the exponentially rising limb of hydrographs (slowly starting and rapidly increasing discharge) measured at several glaciers. It follows from these investigations that the opening of the conduit by frictional heat generated by the water flow and its closure due to viscous ice deformation are likely the controlling processes in many outburst events. However, some outburst events show linearly increasing discharge, which cannot be explained by conduit flow alone. The outburst of Grímsvötn in 1996 is one such event [*Björnsson*, 2002]. Separation of the glacier sole from the bed due to the lake water pressure exceeding the ice overburden, and the subsequent sheet-like water flow through the subglacial space were proposed as an alternative drainage mechanism [*Björnsson*, 1997, 2002; *Jóhannesson*, 2002]. Numerous observations during the 1996 event, including the unusually high lake level, surface uplift of the ice dam, and the development of supraglacial fountains, were consistent with this hypothesis. *Flowers et al.* [2004] showed that a model formulated by the combination of conduits and sheet-like flow can explain the hydrograph of the 1996 outburst from Grímsvötn.

[5] To test the hypotheses described above, it is necessary to gather comprehensive field data during a lake outburst together with topographical information on the ice dam, e.g., ice thickness, bedrock and surface elevation. This paper presents the results of field measurements made during the glacier-dammed lake outburst at Gornergletscher in 2004 and discusses the triggering and drainage mechanisms implied by the observational data. We propose that the outburst was initiated by the flotation of the ice dam and the lake water drained as a sheet-like flow rather than through a single conduit, as indicated by the vertical surface motion of the ice dam.

2. Field Measurements

2.1. Study Site

[6] Gornersee is an ice-marginal lake situated at the confluence area of Gornergletscher and Grenzgletscher in Valais, Switzerland (Figure 1a). Its annual formation in spring and subsequent drainage in summer provide an opportunity to study the outburst mechanisms of a glacier-dammed lake. Most of the lake is ice floored and the eastern margin is dammed by the bedrock. The lake collects surface snowmelt and icemelt over the course of the ablation season and abruptly releases water from a subglacial outlet into the river Gornera, 5 km downstream from the lake. Over the past decades, the outburst has occurred regularly in June or July, whereas the maximum volume of lake water varies significantly from year to year [*Huss et al.*, 2007]. The maximum water volume in 2004 was estimated to be $(4.0 \pm 0.2) \times 10^6$ m^3 on the basis of the lake level and the hypsometry of the lake floor, obtained by processing an aerial photograph taken after the lake was emptied [*Huss et al.*, 2007]. A bed elevation map with 25 m resolution is available for Gornergletscher on the basis of radio-echo soundings carried out in 2004 and 2005 [*Huss*, 2005; *Riesen*, 2007]. Details of the radio-echo soundings and data processing methods are described in the auxiliary material.[1]

2.2. Ice Flow and Deformation Measurements

[7] From May to July 2004, we measured ice motion by surveying aluminum stakes installed in the glacier surface either by an automatic theodolite or GPS (Global Positioning System). The theodolite (Leica TCA1800) installed on the northern flank of the glacier (Figure 1a) was automatically set in operation every hour to survey the three-dimensional positions of the reflectors mounted on stakes 33–36, 41, and 43–47 (Figure 1b). The survey data were corrected by the reference measurement of reflectors fixed

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007JF000920.

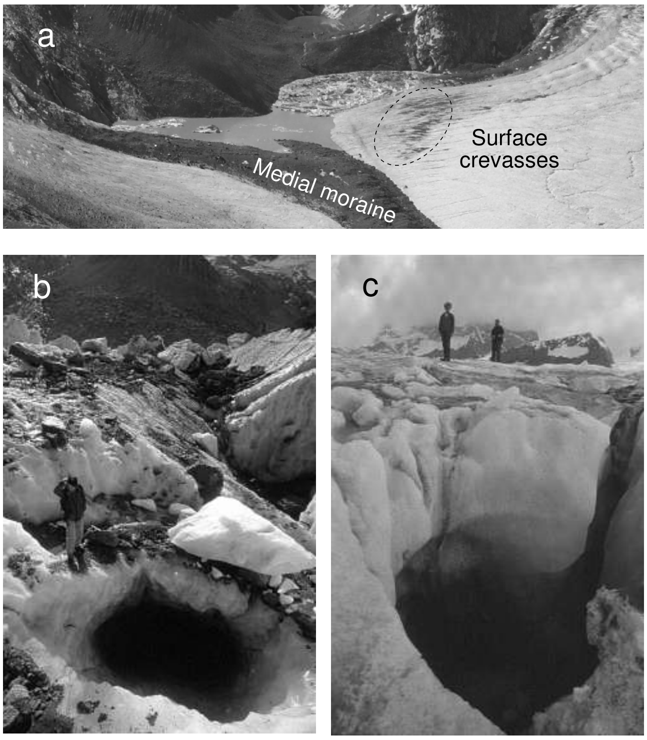

Figure 2. Photographs showing (a) Gornersee viewed from the northern flank of Gornergletscher on 30 June 2007 and (b and c) englacial water channels observed at P1 and P2 in Figure 1b. Figures 2b and 2c by P. Weiss.

on the bedrock. The errors in the angle and distance measurements were ±1″ and $\pm(1 + d \times 10^{-6})$ mm (d: distance in millimeters), which correspond to positional errors from several to 10 millimeters. The accuracy of the relative stake movement in the vertical direction was from ±3 to ±8 mm, depending on the distance from the theodolite to the survey stakes. Owing to the high-frequency measurement, the accuracy can be improved by filtering the data.

[8] Stakes 37 and 42 (Figure 1b) were surveyed by GPS receivers (Leica System 500) mounted on top of the stakes. The L1 and L2 phase signals were recorded eight times a day for static epochs of 1 h at regular intervals of 3 h. The GPS data were postprocessed with the data recorded by the reference receiver installed on the bedrock at the northern flank of the glacier. The accuracy of the GPS survey is estimated to be about 3 and 5 mm in the horizontal and vertical directions, respectively [*Sugiyama and Gudmundsson*, 2004].

[9] High-accuracy borehole length measurements [*Gudmundsson*, 2002; *Sugiyama and Gudmundsson*, 2003] were repeated from 14 June to 12 July to measure the vertical strain of the ice. We drilled a 156 m deep borehole (BH150 in Figure 1b), where the ice is 210 m thick, with a hot water drilling system and installed a ring magnet at the bottom of the borehole. By using a measuring tape equipped with a magnetic sensor on its end, the distance from the magnet to the reference bar installed on the glacier surface was measured once or twice a day. The accuracy of the measurement was estimated as 2–3 mm from repeated measurements [*Gudmundsson*, 2002; *Sugiyama and Gudmundsson*, 2003].

2.3. Hydrological Measurements

[10] Three boreholes (BH430 in Figure 1a, and BH230 and BH210 in Figure 1b) were drilled for subglacial water pressure measurements. According to the length of the drilling hose, the ice thickness at these drilling sites was 430, 230, and 210 m, respectively, with an accuracy of several meters. The water levels in the boreholes were recorded every 10 min by using vibrating wire pressure transducers (Geokon Model 4500) and a data logger (Campbell CR10X). The measurement accuracy was equivalent to a water level of ±0.35 m. The water level data in BH210 was available only until 6 July because of a technical problem with either the sensor or the logger.

[11] The lake water level was measured by a water pressure transducer (Keller, PAA-36W) installed near the deepest point of the lake and recorded every 10 min by the data logger (Campbell CR10X) with an accuracy of ±6 mm. The measurement was terminated when a floating ice block cut the sensor cable during the outburst on 5 July. From the change in the water level and the hypsometry of the lake floor, the discharge rate from the lake was computed for the period of 2–5 July. The error in the discharge due to the uncertainty in the lake floor elevation was about ±5%. To obtain an accurate figure for the lake discharge, changes in the water level due to meltwater input were corrected by using a surface melt model [*Huss et al.*, 2007].

[12] Water discharge from the glacier was measured at approximately 1 km down the valley from the glacier terminus. The Grande Dixence hydroelectric power company operates a water intake system and measures the river discharge every hour.

3. Results

3.1. Lake Outburst

[13] In 2004, the lake began forming in the middle of May, and the lake level increased progressively until the lake basin was completely filled (Figures 2a and 3a). The amount of stored water on 1 July was estimated as $(4 \pm 0.2) \times 10^6$ m^3 from the measured lake level and the known hypsometry of the lake floor. The rate of the water volume increase agrees well with the cumulative meltwater input computed by the surface melt model [*Huss et al.*, 2007], suggesting no significant leakage before the outburst event. The lake level overtopped the ice dam surface on 1 July and the lake water began to flow over the glacier surface prior to the main drainage. On the same day at 1110 h, the water level suddenly dropped by 0.3 m within the measurement interval of 10 min (Figure 3a inset). This incidence indicates the transfer of $(8.0 \pm 0.4) \times 10^4$ m^3 of lake water to subglacial and/or englacial space.

[14] The lake level rose again during the rest of the day, and then the outburst began on 2 July. The lake level began to decrease gradually early in the morning, which was followed by calving of marginal ice at the north of the lake and subsequent increase in the discharge rate. Although the lake level data are available only until 5 July, daily images taken by an automatic camera from Gornergrat (northern flank of Gornergletscher) and visual observations confirmed that the lake was nearly empty on 7 July. The water was draining subglacially at the eastern margin of the glacier during the latter half of the drainage from 5 to 6 July. When

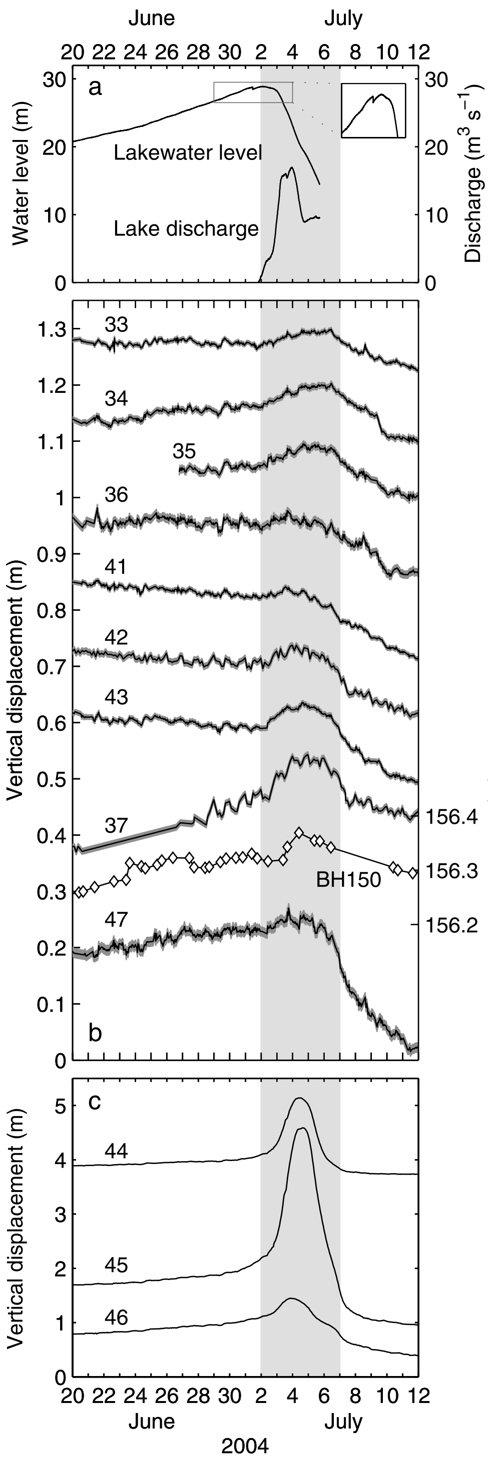

Figure 3. (a) Time series of the lake water level and lake discharge, (b) the vertical displacement and the borehole length change of BH150 (diamonds), and (c) the vertical displacement for the stakes which showed large vertical motion. Six h running mean was taken for the vertical displacement measured by the theodolite and the error estimation for each stake is indicated by the gray band. The vertical gray band indicates the lake outburst period from 2 to 7 July.

the lake emptied out, we found several water channels with diameters of 2–3 m were excavated into the ice (Figures 2b and 2c). These channels were located at horizontal distances of about 5–10 m from the maximum lakeshore and about 2–5 m below the maximum water level. These observations indicate that the outburst occurred via a combination of subglacial and englacial drainage. Englacial water drainage was also confirmed during the event by sensing the vibration of the sensor cable used for the borehole length measurement. From 1800 on 1 July to 1800 on 5 July, a strong water current was detected by the sensor cable vibration as the sensor was lowered in a 120 m deep borehole, which was located at about 5 m from BH150 and BH210, at the depth of 101–103 m from the surface (107–109 m from the bed). The sound of the water flow in the borehole could also be heard. The discharge from the glacier terminus began to increase about a day after the onset of the outburst and it reached a peak discharge on 6 July [*Huss et al.*, 2007].

3.2. Motion of the Ice Dam

[15] During the outburst, all the stakes showed upward motion (Figures 3b and 3c). The magnitude of the vertical displacement was up to 0.1 m except for stakes 44–46 located at the western lakeshore. The displacement at these three stakes was 0.5–3.0 m, 1 order of magnitude greater than at the other stakes (Figure 3c). For the centimeter-scale uplift at stakes 33–37, 41–43, and 47, the initiation of the upward motion coincided with the onset of the outburst. The upward displacement was followed by nearly the same amount of downward displacement during the latter half of the outburst. After the outburst, the general trend of the elevation change was more negative than before the event. At stake 33, for example, the elevation was nearly constant from 20 June to 1 July, but it decreased about 0.05 m from 7 to 11 July. For the greater uplift at stakes 44–46, the initiation was several days earlier than the onset of the outburst and the peak elevation occurred in the middle of the drainage on 4 July. The surface elevation dropped below the preevent level when the lake emptied.

[16] The length of the borehole BH150 generally increased until the lake outburst (Figure 3b). It then began to decrease during the outburst on 4 July and decreased until the end of the measurement process. The mean thickening rate over the upper 156 m was 7.9 ± 0.3 mm day^{-1} (vertical strain rate $\dot{\varepsilon}_{zz}$ = (5.0 ± 0.2) × 10^{-5} day^{-1}) for the period from 20 June to 4 July, whereas it was −10.3 ± 0.5 mm day^{-1} ($\dot{\varepsilon}_{zz}$ = (−6.6 ± 0.3) × 10^{-5} day^{-1}) from 4 to 11 July. The temporal pattern and magnitude of the borehole length changes are comparable to those of the surface vertical motion at the same location (compare with the vertical displacement at stake 37 in Figure 3b), except for the outburst period.

[17] To examine the details of the centimeter-scale uplift during the outburst, linear trends for the period 1–7 July were subtracted from the daily mean surface elevation at stakes 33–37 and 41–43 (Figure 4). This procedure was not applied to stake 47 because the difference between the trends before and after the outburst was too large. The magnitude of the uplift and the time of the peak elevation were different depending on the distance from the lake. The uplift was greater near the lake at stakes 37, 42, and 43.

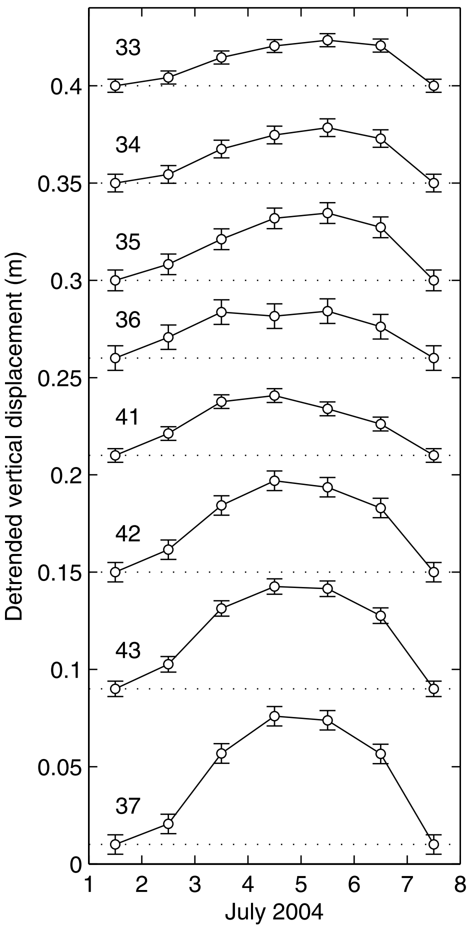

Figure 4. Daily mean vertical displacement at stakes 33–37 and 41–43 from 1 to 7 July. The linear trend from 1 to 7 July is subtracted from the vertical displacement.

Stakes near the lake (41–43 and 37) peaked about a day earlier than those at lower reaches (33–35).

[18] The plan view of the stake motion revealed complex ice flow changes at stakes 44–46 during the outburst event (Figure 5). At the onset of the outburst on 2 July, the direction of the ice flow at stake 44 suddenly changed to the southwest followed by a 180 backward motion lasting until the lake emptied on 8 July (Figure 5a). The horizontal flow speed during 2–8 July was about 1 order of magnitude greater than before and after the lake drainage period [*Weiss*, 2005]. The flow direction after 8 July was northeast, which was clearly different from the preevent direction. The flow changes at stakes 45 and 46 are also very complex, as shown in Figures 5b and 5c. The changes are not exactly the same as those at stake 44, but there are similarities in terms of timing, flow direction and speed. At these three stakes, the first change in the flow direction occurred at the onset of the outburst. The ice began to flow away from the lake until the nearly 180 direction change at around noon on 4 July. The timing of the flow change coincides with the peak in the vertical displacement, which can be recognized by the stake motion projected on the vertical planes (Figure 6). Ice flow speed increased particularly during the second half of the lake drainage from 4 to 8 July. The direction changes and speed up of the ice motion were observed at other stakes as well [*Sugiyama et al.*, 2007], but at 44–46 are much more pronounced. The ice flow directions were toward the empty lake after 8 July, which was substantially different from before 2 July.

3.3. Subglacial Water Pressure

[19] Water levels in boreholes BH430, BH230, and BH210 are shown in Figure 7a with the lake water level, the rate of the lake discharge, and the vertical displacement of stake 45. During the lake drainage period, the water level in BH430 remained at a high level, in contrast to the large diurnal variations prior to the outburst. The water level rapidly dropped on 7 July and it did not rise again to the level before the event. Although these observations represent the clear impact of the outburst on the subglacial water pressure in the confluence area, the other two boreholes located directly in the ice dam are the object of focus here.

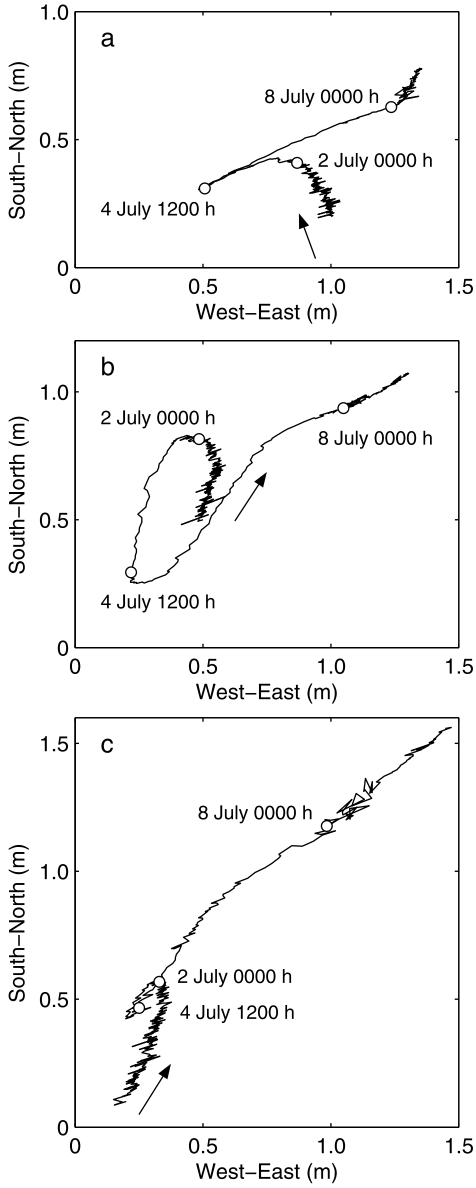

Figure 5. Plan view of the stake motion from 20 June to 12 July at survey stakes (a) 44, (b) 45, and (c) 46. Local time is given to the locations indicated by the open circles.

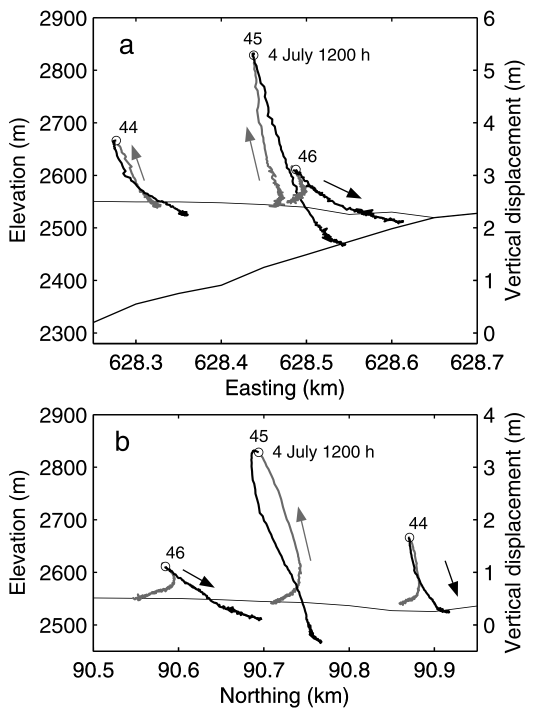

Figure 6. Stake motion projected on (a) west-east and (b) south-north vertical planes intersecting stake 45 with ice and bed surface geometry along the transects. Trajectories before and after 4 July 1200 h (time of the highest elevation) are drawn by the gray and black lines, respectively. The initial positions of the trajectories correspond to the elevation of the stakes.

[20] After the installation of the pressure transducers in BH230 and BH210 the water levels were consistently high and close to the flotation level, probably because the boreholes were not very well connected to the subglacial hydraulic system. Only small diurnal fluctuations were observed as the result of water input from the surface. In these boreholes, water levels dropped on 1 July, the day before the onset of the outburst event. This event approximately coincided with the sudden 0.3 m drop in the lake level. The borehole levels were elevated on 2 July at the onset of the outburst and remained very close to the flotation level during the drainage period. When the lake discharge ceased, the level subsided slowly in BH230, whereas it dropped suddenly by more than 50 m in BH210.

[21] A closer look of the data shows that the features of the precursory event on 1 July are similar in BH230 and BH210 (Figure 7b). The water level in BH210 sharply increased at 0730 h up to several meters higher than the flotation level. Water level in BH230 rose above the flotation level at the same time, which was 2 h earlier than the level increase due to the diurnal variations. The borehole levels dropped at 0940 h about 1.5 h before the 0.3 m lake level change.

4. Interpretation and Discussion

4.1. Vertical Surface Motion

[22] The centimeter-scale uplift observed at stakes 33–37, 41–43, and 47 provide clues to the triggering and drainage mechanisms of the outburst. Vertical motion of a glacier surface is the result of vertical straining, subglacial separation, and the sliding over an inclined bed [*Hooke et al.*, 1989]. The sliding was expected to be enhanced during the outburst, but it cannot explain the upward motion because the bed inclination in the lake vicinity is negative in the flow direction. The effect of the vertical strain can be evaluated by comparing the length change of the borehole BH150 and the vertical displacement at stake 37 (Figure 3b). The lengthening and shortening of the borehole before 2 July and after 7 July show similar trends as the vertical

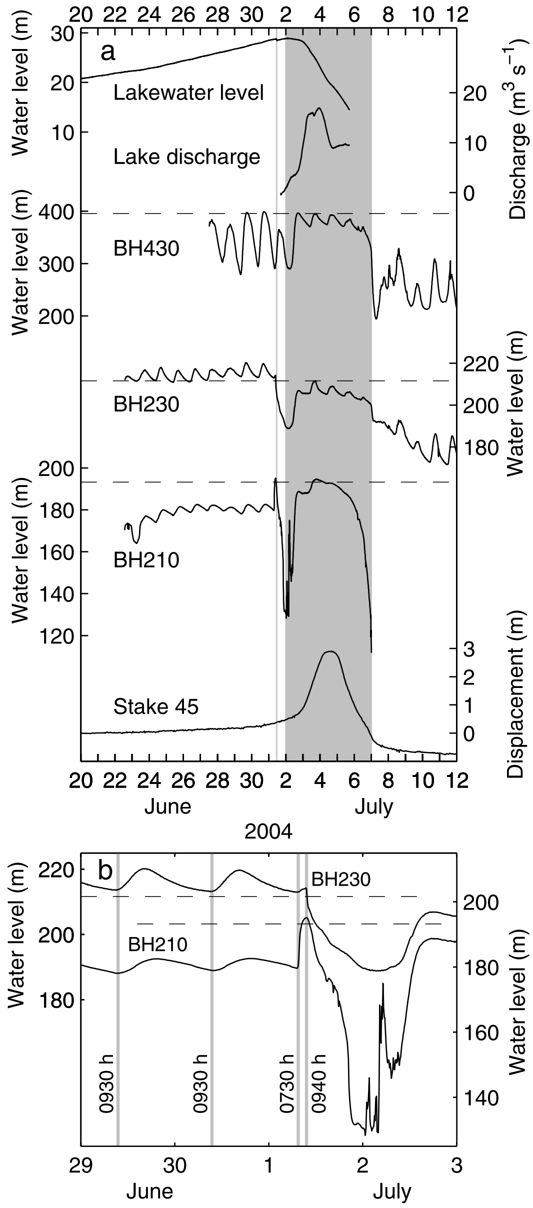

Figure 7. (a) Time series of lake water level; lake discharge; borehole water levels in BH430, BH230, and BH210; and vertical displacement at stake 45. The vertical gray line and the band indicate the timing of the 0.3 m lake level drop on 1 July and the lake outburst period from 2 to 7 July, respectively. The horizontal dashed lines are flotation levels. (b) Detail of the water levels in BH230 and BH210 at the onset of the outburst.

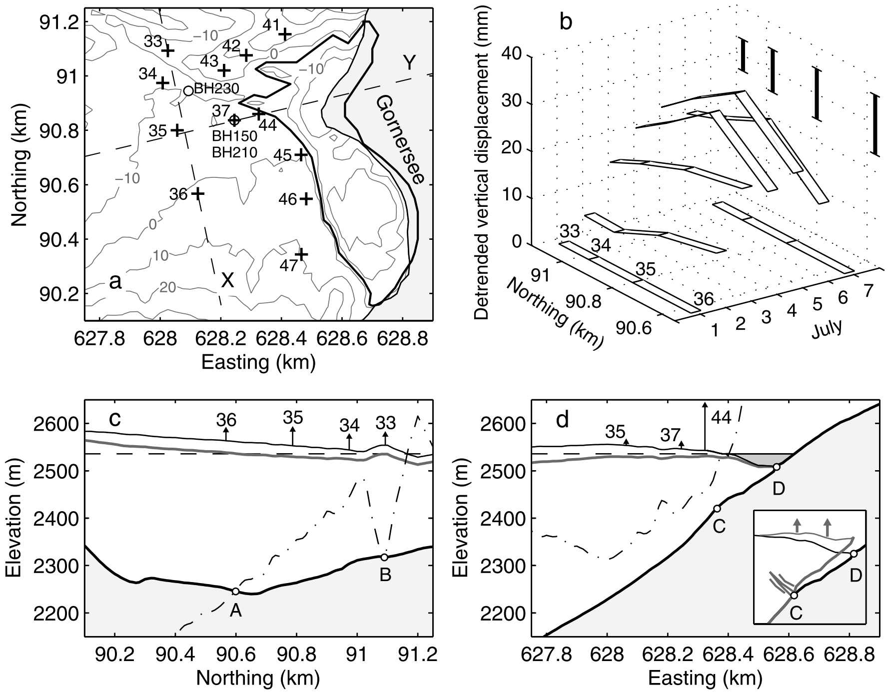

Figure 8. (a) A contour map of Δz as defined by equation (1) at the maximum lake level on 2 July. Locations of the survey stakes and boreholes are indicated by crosses and circles, respectively. The margin of Gornersee is shown by the black line. (b) Vertical displacement at stakes 33–36 from 1 to 7 July. The linear trend from 1 to 7 July is subtracted from the vertical displacement. (c and d) Vertical glacier cross sections along the lines X and Y in Figure 8a with ice surface (thin black line) and bottom (thick black line), lake surface elevation (dashed line), ice flotation level (gray line), and z_b^0 as defined by equation (2) (dashed-dotted line). Locations of the survey stakes are indicated by the arrows and the points A–D are introduced for interpretation (see text). The inset of Figure 8d is a schematic diagram showing the marginal ice bending upward.

displacement on the surface. This indicates that the vertical straining of the ice is an adequate explanation of the vertical surface motion before and after the outburst. Nevertheless, the surface vertical motion from 2 to 6 July is not consistent with the borehole length change, suggesting the occurrence of subglacial separation due to pressurized water. This interpretation is also supported by the water levels in BH230 and BH210 during this period, which were close to the flotation level. The water level data indicate that the subglacial water pressure was high enough to lift the ice in this region. The magnitude of the vertical motion was of the same order at all the survey stakes except for 44–46. The spatially uniform uplift implies that the lake water drained as a subglacial sheet-like flow and the drainage path extended over the studied region. Therefore, we propose ice dam flotation as the triggering mechanism of the outburst and the lake water drainage through the space created between the ice and the bed.

[23] Flotation of the ice dam is likely because the lake water level was higher than the ice surface at one point, thus higher than the ice flotation level. Figure 8a is a contour plot of the difference Δz between the ice flotation level and the lake level z_l on 2 July, described as follows:

$$\Delta z = (z_s - z_b)\frac{\rho_i}{\rho_w} - (z_l - z_b), \qquad (1)$$

where z_s and z_b are the glacier surface and bed elevations (Figures S1 and S2), and ρ_i and ρ_w are ice and water densities. The lake level exceeds the flotation level ($\Delta z < 0$) over part of the ice dam (90.7 km < northing < 91.0 km) and this condition extends down glacier. At these regions, the subglacial water pressure would have been high enough to lift the ice dam when a hydraulic connection between the lake and the glacier base was established. If this was the mechanism of the outburst initiation, the width of the drainage pathway was probably greater than 300 m as the floating part of the ice dam would have pried up the neighboring ice resulting in basal separation over a broader region.

[24] To verify the above interpretation, spatial variation in the surface uplift was examined along the stake profile 33–36. This profile was chosen as it is approximately perpendicular to the assumed drainage pathway. Although the glacier surface motion was influenced by the vertical straining, the greater part of the uplift and subsequent lowering during the outburst was due to the basal separation as shown by the vertical strain measurement in BH150 (Figure 3b). Thus, we use the detrended vertical displacement in Figure 4 as an estimate of basal separation. The uplift occurred evenly at the beginning of the outburst (Figure 8b), implying that the glacier sole was bridging across a subglacial water sheet in a north-south direction. During the second half of the outburst, the vertical dis-

placement was peaked in space at stake 35, suggesting that the drainage was more enhanced at the middle of the profile. These observations support the interpretation that the outburst was triggered by the ice dam flotation over a relatively broad region between 90.7 and 91.0 km northing. If we assume that the maximum lake discharge of about 20 $m^3 s^{-1}$ on 3–4 July (Figure 7) took the form of a subglacial sheet 300 m wide and 20 cm thick (Figure 8b), the peak water flow speed can be estimated roughly as 0.3 $m s^{-1}$.

[25] The location of the peak uplift can be explained by the ice and bedrock geometry. In Figure 8c, the ice flotation level along the line X in Figure 8a is plotted on the glacier cross section together with the lake surface elevation on 2 July. Also indicated is the imaginary ice bottom elevation which is required to satisfy the condition $\Delta z = 0$ for a given ice surface and a lake level [*Nye*, 1976]

$$z_b^0 = z_l - (z_s - z_l)\frac{\rho_i}{\rho_w - \rho_i}. \quad (2)$$

In other words, z_b^0 is the elevation where the hydraulic potential referenced to the lake surface is equal to zero. The comparison of z_b^0 and z_b gives an indication that the ice is floating or grounded where $z_b^0 > z_b$ or $z_b^0 < z_b$, respectively. An interesting feature of z_b^0 is the hydraulic barrier at the point B. The ice overburden pressure is locally high because of the surface mound which is a medial moraine covered with rocks and boulders up to about 1 m thick. The ridge of Δz in Figure 8a along stakes 41–43 and 33 is due to this medial moraine (see Figures 1b and 2a). This ridge might have formed a hydraulic barrier between the lake and the northern part of the glacier. Because this barrier pinned the ice down to the bed, the uplift peak was not at the minimum in the hydraulic potential (stake 34) but at the center of the section AB (stake 35). From the foregoing analysis, we infer that the lake water first drained approximately through section AB in Figure 8c, and elevated water pressure lifted the ice above and in the vicinity of this section. Then, more water drained into the middle of the drainage pathway, forming a drainage center which approximately corresponds to line Y in Figure 8a.

[26] Our observation of surface uplift may be evidence of the triggering and drainage mechanisms proposed for the 1996 jökuhlaup from Grıgrave;msvötn [*Jóhannesson*, 2002; *Björnsson*, 2002; *Flowers et al.*, 2004]. The sharp increase in the lake discharge at the onset of the outburst (Figure 3) is similar to the hydrograph modeled as a sheet discharge [*Flowers et al.*, 2004]. Moreover, the slight increase in discharge from 4 to 5 July after the peak discharge suggests the enlargement of conduits [*Huss et al.*, 2007], which is also consistent with the assumption used in Flowers' model: a sheet flow feeds a nascent system of conduits. The most important feature commonly observed in those two events at Gornersee and Grıgrave;msvötn is a very high lake water level, which is consistent with outburst triggering by ice dam flotation.

4.2. Surface Motion at Stakes 44–46

[27] The timing of the vertical motion at stakes 44–46 is similar to the other stakes, but the large magnitude of the uplift (Figure 3c) and the abrupt direction changes in the horizontal motion (Figure 5) require further interpretation. Figure 8d shows the glacier cross section along the line Y in Figure 8a. The distance from stake 44 to the nearest stake 37 is only 80 m, but the uplift during the outburst is more than 1 m at 44, while it is less than 0.1 m at 37. The increase in the ice surface uplift toward the lake suggests the bending of the marginal ice due to the buoyancy force, as the lake level exceeded the ice flotation level in this region (Figure 8d). Nevertheless, the steep gradient in the vertical displacement from 37 to 44 cannot be explained by the elastic flexure of ice as envisaged by *Nye* [1976]. For a floating ice plate with a thickness of 150 m and a Young's modulus of 10^{10} Pa, a characteristic length scale required to reduce the magnitude of the uplift in an exponential scale can be estimated as 2000 m [*Turcotte and Schubert*, 1982; *Walder et al.*, 2006], which is far greater than the distance between stakes 37 and 44.

[28] The vertical ice motion localized near the lake is similar to that of the observation at Kennicott Glacier [*Walder et al.*, 2005, 2006]. During the filling process of the ice-marginal lake, they observed that the magnitude of the uplift increased toward the lake discontinuously across a 50–100 m wide band which lay approximately parallel to the ice-lake margin. This ice motion was interpreted as the movement of the marginal ice along a high-angle fault. The trajectories of stakes 44–46, however, are too complex to attribute them to the sliding along a fault plane. The uplift was accompanied by the reversal in horizontal motion, i.e., southwest and northeast motion for the periods 2–4 July and 4–8 July, respectively (Figure 5). Thus, the three dimensional trajectory of the stake motion is inclined from a vertical line (Figure 6). Because the azimuth and dip of the trajectory are different for the three stakes, three independent fault systems would have to be assumed to interpret them by faulting. The hysteresis in the trajectories is also difficult to explain by the motion along a fault. The timing of the uplift is clearly different from the observation at Kennicott Glacier. In the case of Kennicott Glacier, the upward surface motion began several weeks before the outburst and it was more correlated with the lake level, suggesting that the ice near the glacier margin was afloat in the lake water [*Walder et al.*, 2005, 2006]. On the contrary, the uplift at Gornergletscher occurred when the lake level was falling and it appeared to be related to the lake discharge with a lag of 1–2 days (Figure 7).

[29] A plausible interpretation of the large uplift at stakes 44–46 is as follows. When the lake water intruded into the bed approximately along the line Y in Figure 8a, the marginal ice went afloat, opposing the thicker part of the glacier which was still grounded. As the resulting stresses in the ice became greater than its mechanical strength, basal crevasses and englacial fractures were formed. Accordingly, the densely crevassed and fractured region enabled the marginal ice to bend steeply upward by acting as a hinge. In Figure 8d, z_b^0 sharply decreases from the margin D to the west and it reaches a local minimum at the point C. This indicates that the buoyancy force acting on the ice above the section CD was much greater than that on the west side of C. Thus, it is likely that many crevasses and fractures were introduced at around the point C and that they caused the upward bending of section CD (Figure 8d inset). The westward motion during the uplift at stakes 44, 45, and 46 (Figure 6a) is consistent with this hypothesis.

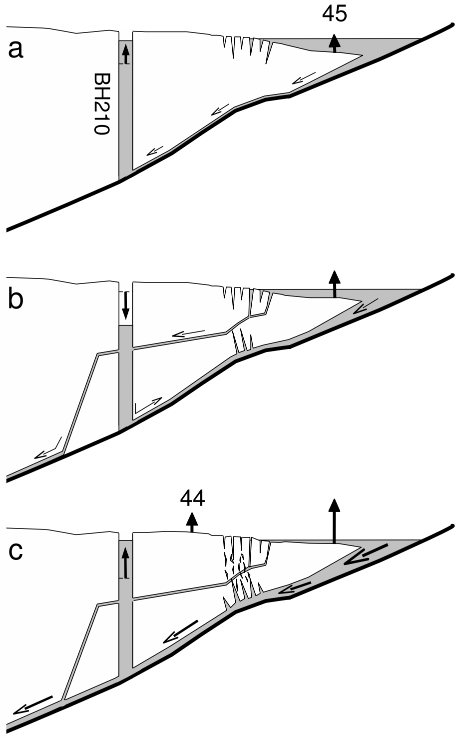

Figure 9. Schematic diagrams showing the triggering and drainage mechanisms of the lake outburst. The diagrams correspond to the conditions when (a) the borehole water levels increased on the morning of 1 July, (b) the water drained englacially on the evening of 1 July, and (c) the subglacial sheet flow was initiated.

The glacier surface is always heavily crevassed near the lake (Figure 2a) because ice flow toward the lake stretches the ice dam in an east-west direction when the lake is empty. These preexisting surface crevasses weakened the ice in the lake vicinity and enabled the large uplift as well.

[30] The magnitude of the uplift appears to be related to the distance from the ice margin, the distance from the suggested drainage center (line Y in Figure 8a), and the ice thickness. The uplift at stake 45 (3.0 m) was the greatest among the surveyed stakes, as it was close to the ice margin and the drainage center, and also the glacier was relatively shallow (110 m ice thickness). The thinner ice causes more uplift as it is expected to be bent more by the buoyancy force. Stake 44 was located approximately on the drainage center, but the uplift was only 1.0 m probably because of the larger distance from the margin and the relatively greater ice thickness (150 m). Presumably, the uplift along the drainage center progressively increases from C to D in Figure 8d. The azimuth of the horizontal ice motion can be explained by the location of the drainage center. The trajectories of stake 45 and 46 are inclined more to the south than that of 44 (Figure 6b), suggesting the ice was pushed away from the line Y (Figure 8a) by the subglacial water intrusion.

4.3. Mechanism of the 2004 Outburst

[31] The foregoing discussion assumes that Gornersee predominantly drained subglacially. However, the water channels excavated into the ice floor indicate englacial drainage as well. It is likely that this englacial and subglacial water flow interacted with the ice-dam motion, that is to say, the ice dam flotation triggered the outburst and the drained lake water induced the surface uplift. Here, we use the observed vertical ice motion, and the lake and borehole water levels to elucidate the details of the link between the outburst and the ice dam motion.

[32] The observational facts relevant to the outburst initiation are listed following in chronological order: (1) on 30 June uplift was detected at stake 45, (2) on 1 July 0730 h water level increased in BH210 and BH230, (3) on 1 July 0940 h water level dropped in BH210 and BH230, (4) on 1 July 1110 h lake water level dropped by 0.3 m, (5) on 1 July 1800 h water flowed englacially near BH210 at the depth of 101–103 m, (6) on 2 July 0230 h lake surface reached the maximum level, and (7) on 2 July 1200 h water level rose up to the flotation level in BH210 and BH230. On the basis of these observations, we propose the mechanism of the 2004 outburst as described below and sketched in Figure 9.

[33] Although the lake level had already been higher than the flotation level at a part of the ice dam, the sole of the ice was in contact with the bed until 30 June. We assume this is because the hydraulic connection of the lake to the glacier bed was insufficient and the stress coupling with neighboring ice prevented the ice dam from flotation. The surface uplift of the ice dam began on 30 June (Observation 1) when the lake water penetrated under the glacier and pried up the marginal ice (Figure 9a). The upward ice-dam motion connected lake water to the glacier bed as indicated by the water level increase in the boreholes in the morning of 1 July (Observation 2). The subsequent drop in the borehole levels (Observation 3) could be attributed to the levering of the ice caused by the elevated subglacial water pressure (Figure 9b). The pressure dropped because of the space created beneath the glacier, which can also explain the sudden drop in the lake level 1.5 h later (Observation 4). Such pressure change controlled by mechanical response of a glacier to a hydrological event was reported by *Flowers and Clarke* [2000] as a result of numerical modeling on a water drainage event in Trapridge Glacier [*Stone and Clarke*, 1996]. At this time, the boreholes were not connected to the ambient drainage system as the water levels did not show the expected diurnal variations (see BH430 in Figure 7a) during the rest of the day. As the uplift rate of the ice dam progressively increased, we hypothesize that cracks and crevasses were formed within the ice dam, which introduced lake water into the glacier body (Figure 9b). The water current detected in the borehole at about 100 m below the surface (Observation 5) confirms that the drainage through englacial water channels preceded sheet flow discharge along the bed. The channel was possibly developed by connecting the englacial cracks and fractures. The hydraulic connection under the ice dam became more pervasive as the uplift proceeded. The discharge from the lake and the subglacial water pressure rapidly increased on 2 July (Observation 7) when the ice dam decoupled from the bed, inducing subglacial drainage as a sheet flow (Figure 9c). The large uplift at stakes 44–46 occurred at this time as the result of levering of the ice

wedge facilitated by crevasse formation and englacial fracturing.

4.4. Outburst Events in 2005 and 2006

[34] We repeated the field observations at Gornergletscher in 2005 and 2006, and found strong annual variabilities in the timing and drainage patterns of the lake outburst. In 2005, the outburst initiated when the lake water volume was less than a third of the full capacity. Detailed examination of the lake level indicated that the water started to leak one week before the outburst and the discharge from the lake increased exponentially [*Huss et al.*, 2007]. We infer from the lake discharge pattern that the lake drained by the process of subglacial channel enlargement. In 2006, water filled the lake without leakage until it started to drain superficially into a moulin located near the lake. The discharge increased as the supraglacial water flow incised a deep gorge on the glacier [*Werder et al.*, 2007]. This drainage process is similar to that observed at Black Rapids Glacier in Alaska [*Raymond and Nolan*, 2000]. From these observations in 2005 and 2006, it is clear that our interpretations for the 2004 outburst are not applicable to these years.

[35] A plausible reason for the annually varying drainage patterns of Gornersee is the condition of the ice dam, which is affected by the previous outburst event. Because of the sudden and large ice motion during the outburst in 2004, it is expected that the ice dam was mechanically damaged by crevasses and cracks. These fractures may not have healed enough to seal the lake water in 2005 and thus caused the leakage before the basin was filled. Accordingly, the impact of the 2005 outburst on the ice dam was relatively small and it might be the reason why the lake did not drain until it was fully filled in 2006. Such an effect has been observed in Grímsvötn, Iceland. The ice dam of Grímsvötn was severely damaged by the catastrophic outburst event in September 1996. After this event, the lake water continuously drained and the lake level could not rise for several years [*Björnsson et al.*, 2001]. Variability in the mechanical condition of the ice dam makes the prediction of the lake outburst more difficult.

[36] Gornersee is floored predominantly by ice rather than bedrock. This lake geometry may contribute to the varying drainage patterns. Buoyancy force is already applied to the marginal ice during the initial stage of lake filling, which may facilitate drainage before the lake is completely filled. The geometry of the lake floor is subjected to more change than that of bed-floored lakes. The timing and location of the outburst may be influenced by the change in the lake hypsometry. For example, if the ice submerged beneath the lake water were thicker, the outburst might be triggered earlier because greater buoyancy force would be exerted on the ice.

5. Conclusions

[37] Detailed measurements of ice-dam motion, combined with hydrological measurements in the lake and adjacent boreholes, are interpreted to describe a plausible mechanism of the 2004 outburst of Gornersee.

[38] The centimeter-scale surface uplift observed pervasively around the lake cannot be attributed to the vertical straining of ice or bed-parallel sliding, thus it suggests the separation of the glacier sole from the bed, which we argue induced a sheet-like outflow from the lake. The magnitude of the uplift was greater at a part of the ice dam where subglacial water pressure would have exceeded the ice overburden pressure if the bed were hydraulically connected to the lake. Thus, hydraulic potential at the bed of the ice dam controlled the location and timing of the outburst. However, the outburst did not just occur when the lake level exceeded the flotation level of the ice dam, because hydraulic connection between the lake and the glacier bed would not be established immediately and the mechanical coupling with neighboring ice would prevent the flotation.

[39] The uplift reached 0.5–3.0 m in the vicinity of the lake. It is likely that englacial fractures, and crevasses at the surface and bottom acted as a hinge which enabled the marginal ice to bend upward. The horizontal ice motion near the lake is consistent with the idea that the lake water drained into a part of the ice dam where the ice overburden pressure was exceeded by the lake water pressure.

[40] Timing of the vertical ice motion and changes in the lake and borehole water levels suggest that the outburst was initiated by drainage through englacial channels, followed by the sheet-like subglacial flow. Presumably, the englacial drainage was induced by newly formed and preexisting crevasses and cracks in the ice dam.

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