Supporting Online Material for

Fracture Propagation to the Base of the Greenland Ice Sheet During Supraglacial Lake Drainage

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Methods and Data

GPS Data

The continuous GPS data were processed at the full 15-s resolution using the Track software (1). The data were processed relative to data from a station on bedrock (Kaga), located approximately 55 km from our lake site. In this processing, site motion was constrained on an epoch-by-epoch basis to suppress noise without damping the signal.

Block uplift

Based on repeated topographic surveys and the timing of GPS surface motion we conclude that the large block in center of the lake (Fig. 1) was uplifted during the lake drainage event in 2006. Sonar surveys of the lake bottom when it was full (July 16, 2006) found no evidence of this feature, although two large, several-meter deep holes were found near the ends of the block’s northern edge (Fig. 1). In May 2006 and then again in May 2007, NASA’s Airborne Topographic Mapper (ATM) flew over the dry lakebed with its scanning laser altimeter (2). The elevation change between the surveys (Fig. 1) indicates ~6 m of surface uplift across the block. The block also is clearly visible in an ASTER satellite image from August 8, 2006 but not visible in earlier imagery. Together, these sources indicate the uplift occurred sometime between July 16 and August 8, 2006. Other than the lake drainage event, the GPS recorded no other substantial uplift on the nearby shore during this period. Thus, we propose that the large volume of water driven beneath the ice sheet during lake drainage likely produced several meters of uplift at the lake’s center concurrent with the meter-scale uplift on the nearby shoreline as recorded by the GPS.

Lake Fill Rate and Volume Calculation

We had several sources of data for determining lake volume. The first of these was a series of sonar surveys performed by boat on July 16, 2006. We also produced a digital elevation model of the region using a nadir- and backward-looking image pair from July 2005 acquired by the Advanced Spaceborne Thermal Emissivity and Reflection Radiometer (ASTER) aboard the Terra satellite. In RADARSAT SAR images acquired shortly after the lake drained, the area recently covered by water appeared far brighter than the surrounding region, which provided us with an estimate of the lake area near the time of drainage. Finally, we installed two internally logging HOBO pressure transducers at two locations on the lake bottom beginning July 17th as well as a third onshore transducer for performing atmospheric pressure corrections to lake level estimates.

We used the DEM to determine the shape of the lake basin, and then adjusted the lake level so that the mean depth agreed with the depths determined by sonar surveys. The standard deviation of the difference between the DEM- and sonar-determined depths was 2.6 m. This procedure gave us an estimated lake volume of 0.019 km$^3$ and surface
area of 4.6 km$^2$ at the time we placed the HOBO loggers in the lake. These instruments measured a 4.9 m increase in lake level over the period leading up to the drainage on July 29 (Fig. S2) during which the SAR image indicated the lake area grew to 5.56 km$^2$. Assuming the lake area grew linearly over this period, then the volume increased by 0.025 km$^3$ to yield a total volume of 0.044 km$^3$ at the time of drainage. Assuming an error in the mean depth of 1 m and digitization error of 125 m for the boundary, we estimate a volume error of 0.01 km$^3$. Over the period the HOBOs logged data prior to lake drainage, meltwater filled the lake at an average rate of 24 m$^3$/s.

1. G. Chen, Ph.D., Massachusetts Institute of Technology (1998).

**Figures**

![Figure S1](image)

**Figure S1.** Velocity (blue and red lines) and relative elevation (black line) for a 24-hour interval that includes the lake drainage event in 2006. These data are smoothed to 2-hour temporal resolution, which reduces the peak values relative to the higher temporal resolution values shown in Fig. 2.
Figure S2. Lake depths from the two HOBO pressure transducers showing lake filling (following installation on July 17, 2006) and lake drainage events in 2006 (green and black) and 2007 (blue and red). Depths are corrected for atmospheric pressure using a third HOBO onshore.
Figure S3. Seismic data from day 210 recorded ~0.7 km north of the lake, with (a) cumulative energy from the vertical channel from 15:00-20:00 UTC, (b) the vertical-channel trace from 15:00-20:00 UTC, and (c) an enlarged view of the vertical-channel trace from 15:00-16:30 UTC. Cumulative energy is the running sum of the squared, normalized amplitude. This cumulative energy curve summarizes the modes and progression of seismic energy release during the day-210 event.

Seismic energy is observed in two modes, a rumbling mode and a discrete cracking or ice-quake mode. Discrete cracking events release a large amount of energy in a small amount of time and are seen as steps in the cumulative energy curve and as large amplitude deflections in the seismic trace. Prominent
examples are indicated by the dashed lines. It may be possible to relate these cracking events to key events in the evolution of lake drainage, such as the initial crack propagation and the uplift and/or subsequent settling of the central block, but analyses of the seismic data are too preliminary at present to rigorously support such interpretations.

The rumbling mode of energy release is manifest as more or less continuous increases in the cumulative energy curve, with the slope of the curve related to the intensity of the "rumbling". The initial rapid-drainage phase between 16:00-16:30 UTC is associated with a distinct seismic signal (c) that was seismically quiet relative to subsequent phases of the drainage event. Continuous rapid drainage between 16:30-17:30 UTC was more energetic, yielding a distinct slope in the cumulative energy curve. This slope is offset at ~17:20 UTC by a discrete event that may be related to the central block uplift.

The end of the rapid-drainage phase at ~17:30 UTC is marked by a distinct change in cumulative energy slope, indicating a change to a "noisier" phase of drainage. We speculate that the increased rumbling during this later phase indicates water falling into the now incompletely full crack and ice settling following the period of uplift.