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Greenland subglacial lakes detected by radar

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[1] Subglacial lakes are an established and important component of the basal hydrological system of the Antarctic ice sheets, but none have been reported from Greenland. Here we present airborne radio echo sounder (RES) measurements that provide the first clear evidence for the existence of subglacial lakes in Greenland. Two lakes, with areas ~8 and ~10 km^2, are found in the northwest sector of the ice sheet, ~40 km from the ice margin, and below 757 and 809 m of ice, respectively. The setting of the Greenland lakes differs from those of Antarctic subglacial lakes, being beneath relatively thin and cold ice, pointing to a fundamental difference in their nature and genesis. Possibilities that the lakes consist of either ancient saline water in a closed system or are part of a fresh, modern open hydrological system are discussed, with the latter interpretation considered more likely.
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1. Introduction

[2] Subglacial lakes are important because their presence influences ice motion [*Stearns et al*., 2008] and, possibly, the initiation of fast-flowing ice streams [*Bell et al*., 2007]. They are also among the most extreme viable habitats on Earth [*Siegert et al*., 2001]. Since the first Antarctic subglacial lake was detected nearly 50 years ago [*Robin et al*., 1970], 379 subglacial lakes have been identified throughout the continent [*Wright and Siegert*, 2012]. The majority of these lakes were discovered using RES and are typically found in close proximity (<200 km) to ice divides, the boundaries between ice sheet drainage basins. The remaining lakes were detected beneath or adjacent to fast-flowing ice streams using satellite altimetry [*Ridley et al*., 1993] and interferometric synthetic aperture radar (InSAR) [*Gray et al*., 2005]. These altimetric and InSAR observations reveal substantial loss and/or gain of water and, consequently, a highly active basal hydrology in some places [*Fricker et al*., 2007; *Smith et al*., 2009]. No lakes have been reported from beneath the Greenland ice sheet, however, despite the previous close examination of RES data from surveys covering this ice sheet with a higher flightline density compared to most surveys in Antarctica [*Oswald and Gogineni*, 2012]. The absence of subglacial lake detections in Greenland may be related to subglacial lake instability [*Pattyn*, 2008], as well as the effectiveness of the Greenland ice sheet at transferring subglacial water to the ice sheet margin [*Livingstone et al*., 2013]. The inability of RES to detect water through its backscatter amplitude if water depths are less than ~10 m thick [*Gorman and Siegert*, 1999] and may additionally explain why small lakes are not easily identified. Here through analysis of airborne RES measurements acquired across the northwest Greenland ice sheet in May 2012, we present evidence for two subglacial lakes that satisfy established subglacial lake detection criteria [*Siegert et al*., 1996].

2. Methods

[3] To obtain RES measurements of ice thickness, we used a Basler BT-67 aircraft equipped with the University of Texas Institute for Geophysics High-Capability Radar Sounder-2 (HiCARS-2) [*Peters et al*., 2005]. Radar data were acquired on 10 May 2012 along flightlines shown in Figure 1a. Data were processed using pulse limited SAR focusing [*Peters et al*., 2007]. Radargrams were then interpreted interactively to identify ice surface and subglacial echoes, yielding ice thickness over the survey region. Point measurements of ice thickness were interpolated using a natural neighbor algorithm to a 500 m regular grid in a polar stereographic map projection. Subglacial bed elevation was then derived by subtracting the interpolated ice thickness data from the Spot5 stereoscopic survey of Polar Ice: Reference Images and Topographies[*Korona et al*., 2009] ice surface elevation model, after first applying a geoid correction. In order to improve data coverage in the study area, we supplemented our radar measurements with data acquired by the University of Kansas Multichannel Coherent Radar Depth Sounder instrument [*Gogineni et al*., 2001]. These data were acquired on the same day as our RES data, during NASA's Operation IceBridge mission [*Leuschen*, 2013].

3. Results

[4] The presence of pooled basal water is indicated by basal radar reflectors that are bright (~10–20 dB higher than from surrounding bed regions), flat, and specular (Figure 2). These reflectors closely resemble those from well-known Antarctic deep water subglacial lakes, such as Lake Vostok [*Oswald and Robin*, 1973], which gives us confidence in our interpretation. The radar transect shows that Lake 1 (L1) is

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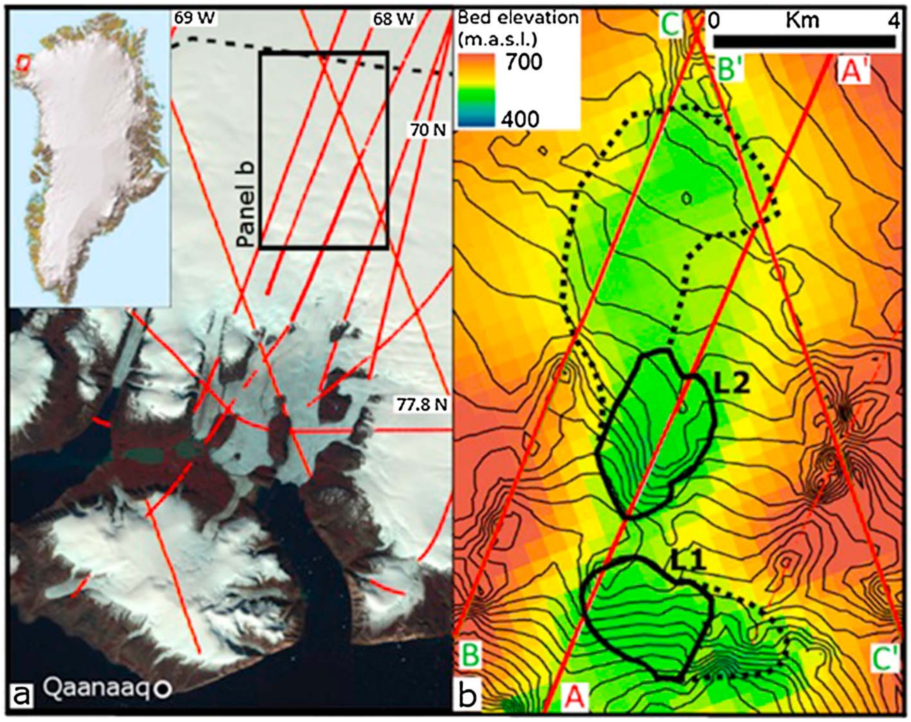

Figure 1. Flight-line map and derived bed elevation from northwest Greenland. (a) Regional context of the study area shown on a Landsat image acquired on 1 August 2002, showing radar flightlines (red lines), the ice divide (dashed black line), and the settlement of Qaanaaq (white circle). (b) Subglacial bed elevations (color) derived from airborne ice thickness measurements along flightlines. Black lines delineate contours of basal hydraulic potential; thick black lines show the inferred extent of observed subglacial lakes; and dashed black lines show possible previous larger extent. Radargrams for the labeled flightlines are shown in Figure 2.

>1.1 km long and Lake 2 (L2) is > 2.4 km long. The lakes are located in a 980 km^2 drainage basin and positioned 16.0 km and 11.5 km from the nearest ice divide, respectively (Figure 1b). Furthermore, they reside in topographic minima separated by a 200 m high, 2.5 km long ridge. The mean (above sea level) lake-surface elevations (±1σ) are 559 ± 4 m at Lake 1 and 560 ± 8 m at Lake 2, whereas the overlying ice thicknesses are 757 ± 4 m and 809 ± 6 m, respectively. In the center of L2 there is a 43 m long topographic feature with a mean elevation of 565 ± 2 m that exhibits a 10 dB lower radar echo strength, indicating the presence of a subglacial island (Figure 2). Such features have been found in deep Antarctic lakes, for example, Lake Vostok [*Siegert et al.*, 2001]. We detect the subglacial lakes on a single radar transect, so we are unable to determine if the lakes are in hydrostatic equilibrium with the overlying ice because the angle between the maximum lake surface slope and flightline orientation is unknown. As horizontal lake extents are of the order of two ice thicknesses, bridging stresses within the overlying ice may prevent hydrostatic equilibrium from fully developing. Using the radar information to specify bed topography, we estimate the lake areas to be ~8 km^2 for L1 and ~10 km^2 for L2 (Figure 1b). Radar surface echo strengths are consistent with dry firn at the surface when the line was flown.

[5] Bed reflectance data for the primary flightline, shown in Figure 2, were derived from the raw HiCARS-2 bed echoes by applying a constant ice attenuation correction of 45 dB km^{-1}. Although englacial ice attenuation varies spatially [*Matsuoka*, 2011], we do not expect such variation to be important in our study area, where slow flow cannot induce large spatial variation of temperature within the ice.

[6] The physical setting of the two Greenland subglacial lakes is compared with that of the rest of the Greenland ice sheet bed (Figure 3), focusing on geothermal heat flux estimated from satellite magnetometry [*Maule et al.*, 2005], ice thickness from RES measurements, ice surface slope [*Bamber et al.*, 2013], and ice surface flow speeds [*Joughin et al.*, 2010]. Whereas values of geothermal heat flux and ice flow speed at L1 and L2 are typical for the Greenland ice sheet, values of ice thickness and ice surface elevation fall outside the 75th percentile of the ice-sheet-wide distributions (Figure 3), which is unsurprising given the proximity to the ice margin.

[7] The same comparison was made between the settings of L1 and L2 and the Antarctic drainage basins comprising the “Southern Transantarctic” region (hereinafter “ST basin” following *Zwally et al.* [2012]), in which 145 subglacial lakes have been identified so far [*Wright and Siegert*, 2012]. The ST basin has an area of ~1.7 M km^2, similar to that of the entire Greenland ice sheet. We found that heat flux values at L1 and L2 are higher than the 75th percentile of the distribution of values for these Antarctic subglacial lakes. By contrast, ice thickness and ice surface slopes measured above L1 and L2 are at the extreme lower end and extreme upper end, respectively, of the distribution of values for Antarctic subglacial lakes. Assuming that basal water pressure is equal to the ice overburden pressure [*Shreve*, 1972], this leads to values of basal hydropotential gradient at L1 and L2 3 to 4 times larger than the highest hydropotential gradients at known subglacial lakes in the ST

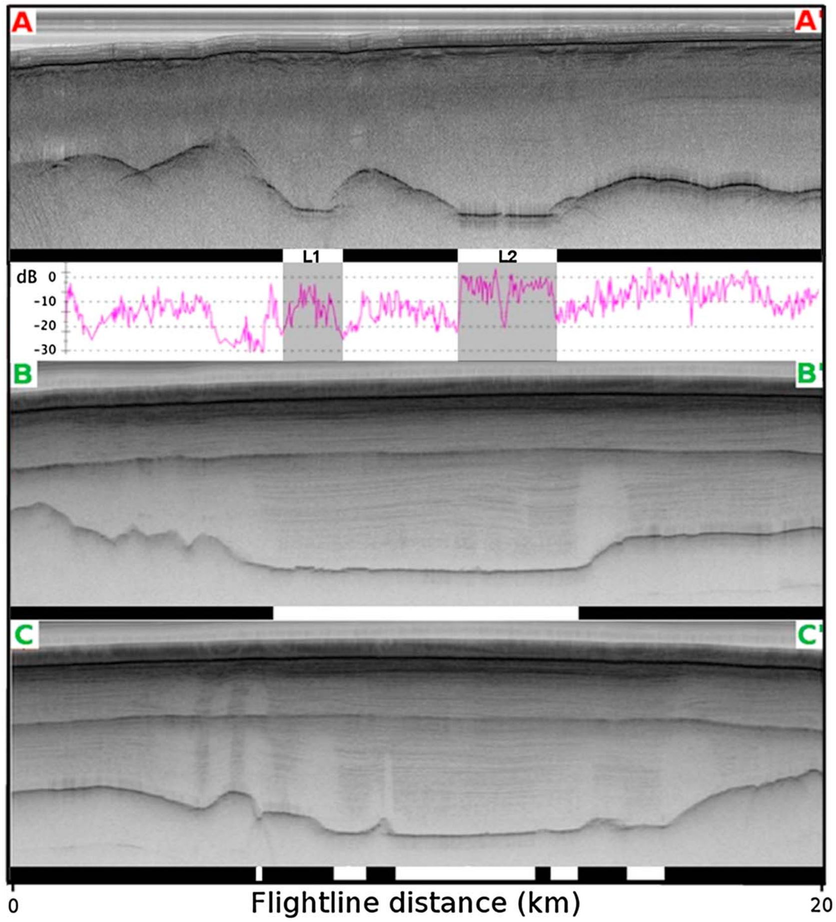

Figure 2. Radar evidence for subglacial lakes. Radargrams showing data acquired along flightlines labeled in Figure 1, showing subglacial lakes (L1 and L2) on profile A-A′ (GOG2/F04T01a), with bed reflection strength shown below. Areas of subhorizontal and brightly reflecting bed on profiles B-B′ (20120510_01_035) and C-C′ (20120510_01_074) are indicated by white bars below the radargrams. These areas could indicate the presence of saturated sediment at the bed and therefore may indicate previous subglacial lake extent.

basin. The physical setting of L1 and L2 is, therefore, unusual compared to the typical settings of both the Greenland and Antarctic ice sheets.

[8] To investigate the thermal setting around L1 and L2, we calculate the steady state ice temperature profiles above each lake using an analytical expression for ice flowing solely by internal deformation [*Robin*, 1955] and a Clausius-Clapeyron gradient of 8.7×10^{-4} °C m^{-1} [*Paterson*, 1994]. Using the mean ice surface temperature for the period 2000–2010 derived from NASA's Moderate Resolution Imaging Spectroradiometer instrument (−22°C) [*Hall et al.*, 2013], an accumulation rate of 0.3 m yr^{-1} from a regional climate model [*Ettema et al.*, 2010] and a geothermal heat flux estimate of 60 mW m^{-2} [*Maule et al.*, 2005], the basal temperatures would be ~ −8°C at the lake locations, i.e., well below the pressure-dependent melting point (−0.7°C). Under such conditions, ice around the lakes would be frozen to the bed and the lakes would therefore be hydrologically isolated and form closed systems, which could explain their preservation. Due to the large uncertainties in geothermal heat flux in Greenland, and the fact that high values (>100 mWm^{-2}) have been inferred from RES data in the central and northeastern part of the ice sheet [*Fahnestock et al.*, 2001], we cannot rule out the possibility that the geothermal heat flux is higher than 60 mW m^{-2} in the study area. However, the low ice flow speeds above the lakes (6 m yr^{-1} and 15 m yr^{-1}; Figure 3) are consistent with motion due to internal deformation alone, which suggests that the ice around L1 and L2 is below the pressure-melting point (i.e., frozen to the bed).

4. Discussion

[9] There are two main possibilities for the presence of the subglacial lakes we have detected in the northwest part of the Greenland ice sheet, linked to the presence of either a closed or open hydrological system at the bed. In the first case, the lakes might resemble that found beneath 450 m of ice, 4 km from the terminus of Taylor Glacier in the McMurdo Dry Valleys, East Antarctica [*Hubbard et al.*, 2004], a region where mean annual surface temperatures (−17°C) and basal temperatures (−8°C) are similar to those in our study area. The Taylor Glacier subglacial lake consists of brine that may have been cryoconcentrated to ~1375 mM prior to isolation from direct contact with the atmosphere, about 1.5 Ma ago [*Mickuchi et al.*, 2009]. Geochemical and DNA analyses of this brine following an outburst event show that it supports a metabolically active, largely marine microbial assemblage. If L1 and L2 were formed through a similar process, they may have been isolated since the region was last overridden by ice, which is likely to be following the Eemian

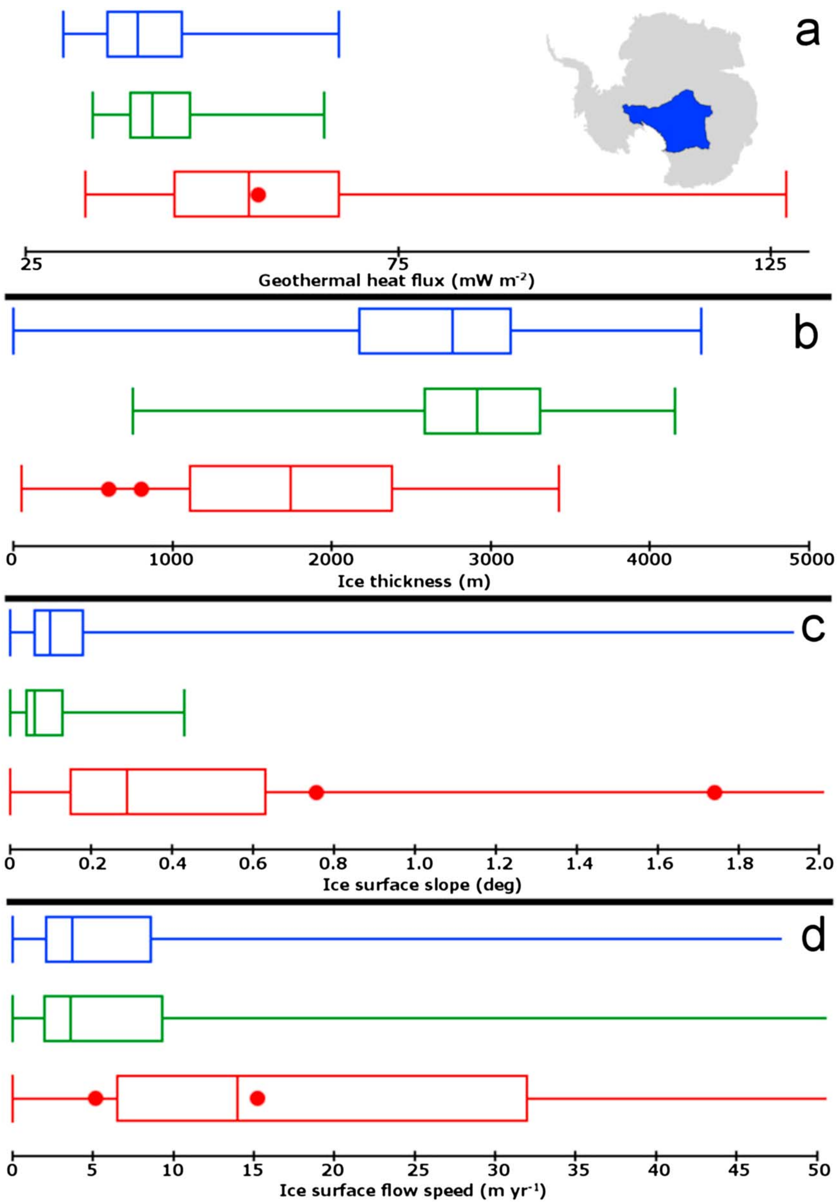

Figure 3. Boxplots showing distributions of (a) geothermal heat flux, (b) ice thickness, (c) ice surface slopes, and (d) ice surface flow speeds for the ST basin (blue), the 145 known ST basin subglacial lakes (green), and the Greenland ice sheet (red). Half of each distribution lies within the "boxes," with the median value represented by the central vertical line. The lowest 25% of each distribution lies to the left of the "box" and the highest 25% to the right. The values of each parameter for the subglacial lakes we report are shown as red circles. Shown inset in blue is the location of the ST basin.

interglacial, 135–115 ka BP [*Funder et al*., 2011]. We estimate that the salt concentration must be at least ~1900 mM (roughly 3 times the salinity of seawater) for the brine to have a freezing point of −8°C.

[10] RES data acquired on flightlines adjacent to the primary flightline (Figure 2) reveal areas of "wet-bed" surrounding the subglacial lakes, identified by their subhorizontal, highly reflective character. This raises the possibility that L1 and L2 were once up to 3 times larger than their current extent and suggests they contain spare capacity for additional water storage. Such a contraction of lake extent may have occurred through the process of basal ice accretion, which, in a closed system, would increase the salinity of lake water due to rejection of solutes by freezing. The rate at which solutes are rejected by basal ice accretion is, however, insufficient to explain the required high level of salinity needed for the lakes to form a closed system in thermal equilibrium at −8°C. Thermodynamic modeling of a freezing subglacial environment beneath slow-moving ice in a similar environment yields an increase in salinity of just a few per mille over the last glacial period [*Christoffersen and Tulaczyk*, 2003]. Hence, if the lakes form a closed system of saline water, the high salinity should have been attained prior to the last glaciation. The most obvious source of such water is the sea, but given the lakes present elevation at >500 m above sea level, it is unlikely that the sea had access to these lakes at any time since the Eemian interglacial.

[11] A second possible reason for the presence of the subglacial lakes is that they form an open system, with basal freezing sustaining by inputs of supraglacial water from the

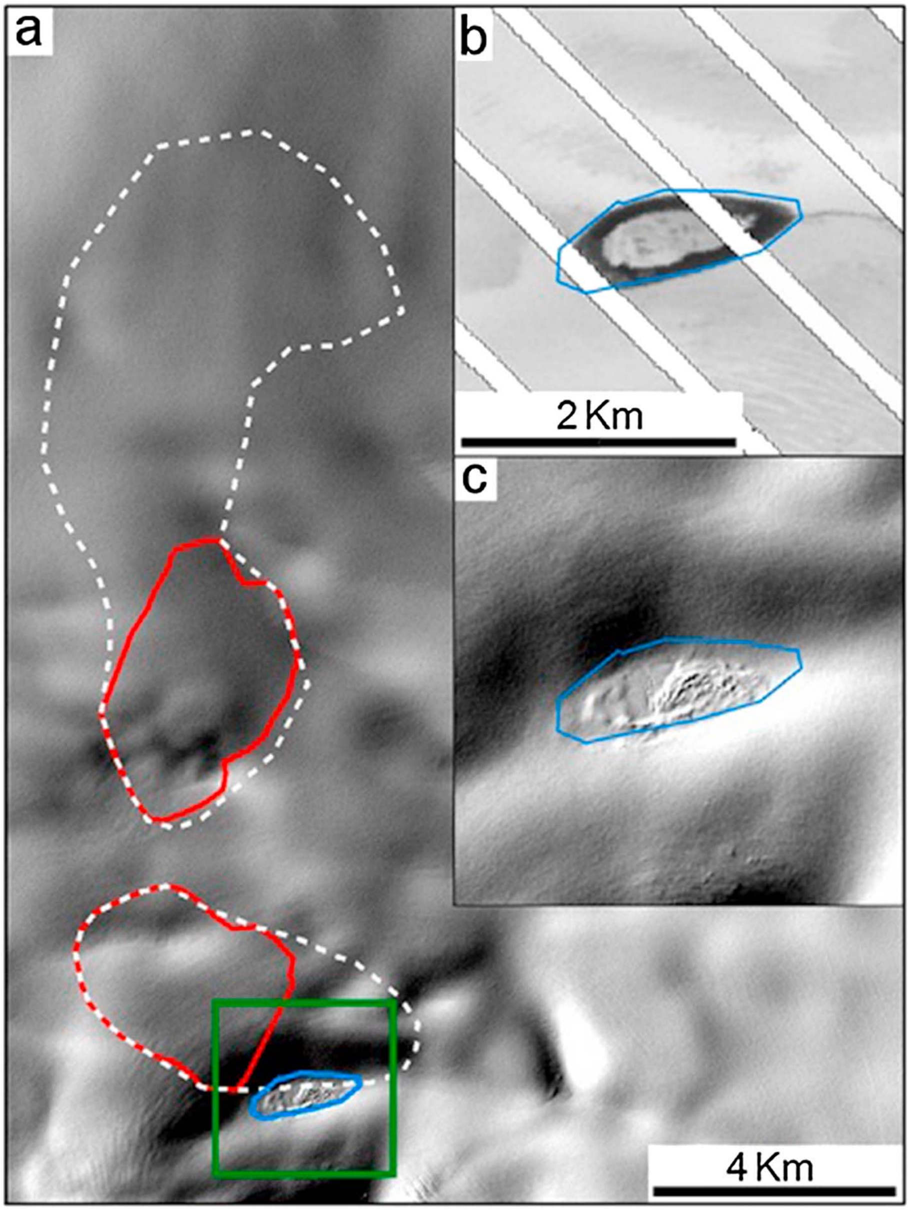

Figure 4. Evidence for supraglacial lake drainage in the study area. (a) Detected subglacial lakes (red outline) with possible previous extent (white dashed) and outline of a supraglacial lake (solid blue outline in green box) shown enlarged in panels (b) and (c). The background image in panels Figures 4a and 4c is a 15 m resolution panchromatic Landsat 8 image acquired on 29 May 2013. The Landsat 7 image in Figure 4b was acquired on 18 July 2012 and shows a supraglacial lake with a partially frozen "lid" (stripes due to a scanner malfunction). Complex ice terrain at the supraglacial lake surface in Figure 4c provides evidence that this lake has catastrophically drained over the course of the year.

ice sheet surface. Archival Landsat data reveal a ~0.8 km^2 supraglacial lake within 1 km down ice flow of the location of L1 on 18 July 2012 (Figure 4) and Moderate Resolution Imaging Spectroradiometer-derived observations of ice sheet surface temperatures indicate that the ice sheet above the subglacial lake experienced several days of melting each year during the period 2000 to 2012 [*Hall et al.*, 2013]. Surface meltwater is known to reach the bed via the process of hydrofracturing following supraglacial lake drainage [*Das et al.*, 2008], presenting the possibility that the subglacial lakes are sustained by freshwater derived from the ice surface. Assuming an average water depth of 2 m, this supraglacial lake could hold 1.6×10^6 m^3 of water, sufficient to propagate a fracture through 800 m of ice to the bed [*Krawczynski et al.*, 2009]. As the supraglacial lake is down ice flow of L1, the water would need to be routed down a steep reverse slope, up ice flow, to the lake. Such bed relief is seen in our radar data downstream of L1, suggesting the routing of water from the surface to L1 via the bed is possible. Furthermore, complex ice terrain at the surface of the supraglacial lake, shown in Figure 4, provides evidence that the supraglacial lake drained in the recent past.

[12] Given the low basal ice temperatures, an additional source of heat would be required to sustain fresh water at, or above, the local freezing point. We exclude frictional heating as a viable heat source because the low surface velocities are consistent with motion due solely to internal deformation. However, a freezing rate of 6 mm yr^{-1} across the

surfaces of L1 and L2 would provide sufficient energy through latent heat of fusion to sustain fresh water at the local melting point (−0.7°C). If the nearby supraglacial lake were to drain completely to the bed every 15 years or less, it would replenish the subglacial lakes at a rate sufficient to balance this freezing rate; thus, in this interpretation, the lakes are part of the modern open hydrological system of the ice sheet.

[13] While the previous lack of RES evidence for subglacial lakes in Greenland is not evidence of their absence, it appears from existing radar data that such lakes are much less common than in Antarctica. The setting of the subglacial lakes reported here point to cold thermal conditions, surface-meltwater inputs, and inefficient drainage as key criteria for the formation of subglacial lakes in Greenland. The relatively large supply of surface meltwater to the base of much of the Greenland ice sheet through surface-lake hydrofracturing and drainage may mean that a greater proportion of the Greenland ice sheet is underlain by a drainage system that is more efficient than that beneath much of Antarctica, implying that subglacial lake development is restricted spatially.

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