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Vertical extension of the subglacial drainage system into basal crevasses

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Water plays a first-order role in basal sliding of glaciers and ice sheets and is often a key constituent of accelerated glacier motion[1–4]. Subglacial water is known to occupy systems of cavities and conduits at the interface between ice and the underlying bed surface, depending upon the history of water input and the characteristics of the substrate[5]. Full understanding of the extent and configuration of basal water is lacking, however, because direct observation is difficult. This limits our ability to simulate ice dynamics and the subsequent impacts on sea-level rise realistically. Here we show that the subglacial hydrological system can have a large volume of water occupying basal crevasses that extend upward from the bed into the overlying ice. Radar and seismic imaging combined with *in situ* borehole measurements collected on Bench Glacier, Alaska, reveal numerous water-filled basal crevasses with highly transmissive connections to the bed. Some crevasses extend many tens of metres above the bed and together they hold a volume of water equivalent to at least a decimetre layer covering the bed. Our results demonstrate that the basal hydrologic system can extend high into the overlying ice mass, where basal crevasses increase water-storage capacity and could potentially modulate basal water pressure. Because basal crevasses can form under commonly observed glaciological conditions, our findings have implications for interpreting and modelling subglacial hydrologic processes and related sliding accelerations of glaciers and ice sheets.

Glacier sliding motion is frequently tied to the geometry and flow conditions of water at the ice–bed interface. The geometrical configuration of the basal hydrologic system has largely been inferred from point measurements in boreholes[6], moulins[7] and access tunnels[8], or inspection of the bed after deglaciation[9]. The vertical extent of the bed drainage system is typically defined by the geometry of basal cavities and conduits—water within the overlying ice is considered part of an englacial system delivering water to the bed. Where basal crevasses propagate upward from the bed, however, they may extend the bed drainage system into overlying ice because the water-filled fractures are well connected to the bed but do not intersect the surface.

Basal crevasses can form in grounded glaciers with longitudinally stretching ice and/or high basal water pressure. Where bed water pressure is equivalent to ice overburden pressure, no ice extension is required to form basal crevasses many tens of metres high, and stretching rates of less than 0.01 per year allow crevasses to propagate over 100 m above the bed[10]. These conditions are probably not widespread, temporally or spatially, under most glaciers and ice sheets. Nevertheless, basal water pressure at or very near the ice overburden pressure has been documented in differing glaciological settings including temperate[11] and polythermal[12] glaciers, and the Greenland[13] and Antarctic[14] ice sheets. Basal crevasses are therefore possible in many glaciers and ice sheets, albeit restricted to certain locations or select time intervals. To test whether basal crevasses are an important component of the basal hydrological system, we combined *in situ* borehole experiments with intensive geophysical imaging of the interior and bed of an Alaskan glacier.

We conducted field experiments on Bench Glacier, a temperate valley glacier about 7 km long and up to ~200 m thick. During the springs of 2003 and 2006 we drilled and instrumented 28 boreholes to the base of the ice at locations spanning about 0.5 km of the ablation zone (Fig. 1). All boreholes were hot-water drilled using equipment and procedures that create a near-vertical borehole about 12 cm in diameter[15]. Borehole water levels during spring indicate that basal water pressure was at or near ice overburden pressure (Supplementary Fig. 1) and surface velocity measurements indicate that the ice frequently experienced >0.02 per year of extending flow[16].

Detailed video inspection of 25 boreholes just after they were drilled revealed that each hole intersected an average of 2.0 water-filled englacial fractures. A crevasse-free glacier surface and the fact that no englacial fractures were observed in the upper 50 m of ice (Supplementary Fig. 2), together imply that the open fractures observed at depth did not intersect the surface. Englacial fracture apertures ranged from a few centimetres up to nearly a metre, and the average was about 4 cm.

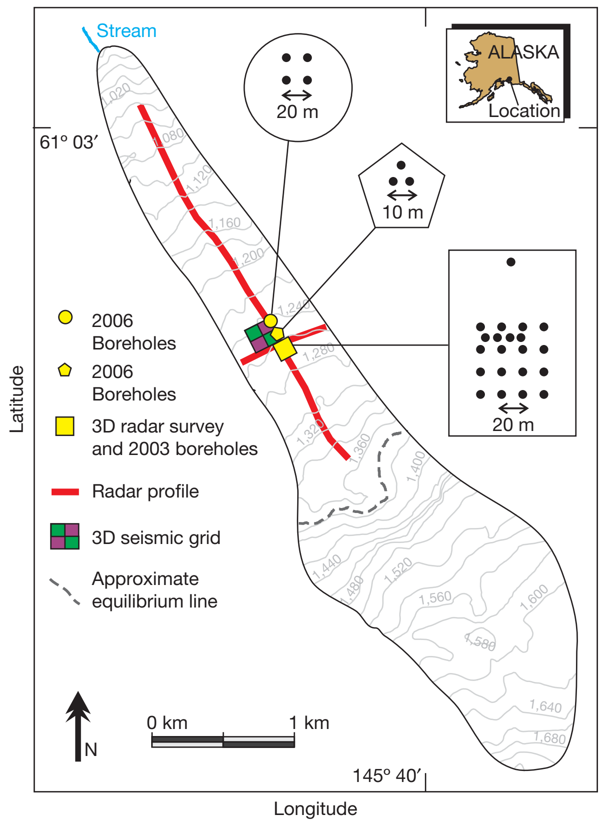

Figure 1 | Map showing Bench Glacier, Alaska, and location of borehole and geophysical measurements. Boreholes having detailed video logs are shown, with locations of geophysical measurements. (Contours are marked in metres.)

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Fractures dipped by at least 70°, and their planform orientation was 30°–50° from the along-glacier flow line. We found no correlation between depth and aperture or distribution. Our sampling, however, is strongly biased towards the surface because turbid water near the base of the boreholes limited or prevented viewing.

Monitored-drilling experiments documented strong hydraulic transmissivity between englacial fractures and the bed. The water levels in a network of up to six boreholes spaced 10–60 m apart were monitored while drilling a new borehole through the glacier (see Methods). Sudden, large changes in borehole water levels during drilling indicate that the advancing drill-hole intersected an englacial water-routeing pathway. During eight of nine drilling experiments the drill hole suddenly drained by up to 14 m while the drill hole was advancing through the lower half of the glacier (Supplementary Table 1). The drill holes drained at rates of up to 0.63 $m^3 s^{-1}$ (Fig. 2) until their water levels equalled the level in nearby boreholes that intersected the bed. The draining events always occurred where the drill-tip intersected an open fracture visible in subsequent borehole video inspection. The very steep dip of fractures implies that connections were direct to the bed. Not every fracture identified in the video, however, could be associated with a draining event. Dye-tracing experiments using a pair of borehole fluorometers confirmed that fractures rapidly transmitted water (Supplementary Fig. 4).

Boreholes located up to 60 m adjacent to drill holes experienced sudden water level changes (usually rising) when the englacial base of the drill hole intersected a fracture connected to the bed. There were no lag times between water level changes in the drill hole and each of the adjacent holes. Changes also occurred at similar rates, implying highly transmissive connections between the fracture in the drill hole, the bed and other boreholes (Fig. 2). The total volume of water gained in adjacent holes was 20–60% less than the volume lost in drill holes, indicating that water leaked to other parts of the hydrological system. In two cases, sudden rising water levels were observed in all holes (including the drill hole) with continued drilling after a draining event. These events were also associated with a fracture identified in the video, which presumably had higher hydraulic head than the boreholes.

Radar and seismic imaging add supporting evidence that water-filled fractures were common at depth but not near the surface. Profiling measurements reveal radar scattering from water-filled features with one dimension exceeding a metre and located at depths of 20–50 m below the ice surface[17], although the two-dimensional (2D) diffractions alone poorly constrain the geometry of scattering bodies. Densely spaced three-dimensional (3D) radar data (see Methods), however, show events deep within the ice mass that are laterally coherent over tens of metres, and that therefore resemble fractures (Fig. 3). Both elastic and electromagnetic waves propagating from the surface should exhibit azimuthally dependent velocities owing to fractures having a preferred orientation. We therefore tested for azimuthal velocity anisotropy with multi-azimuthal 3D seismic reflection and georadar experiments (see Methods). Elastic Rayleigh-wave data show

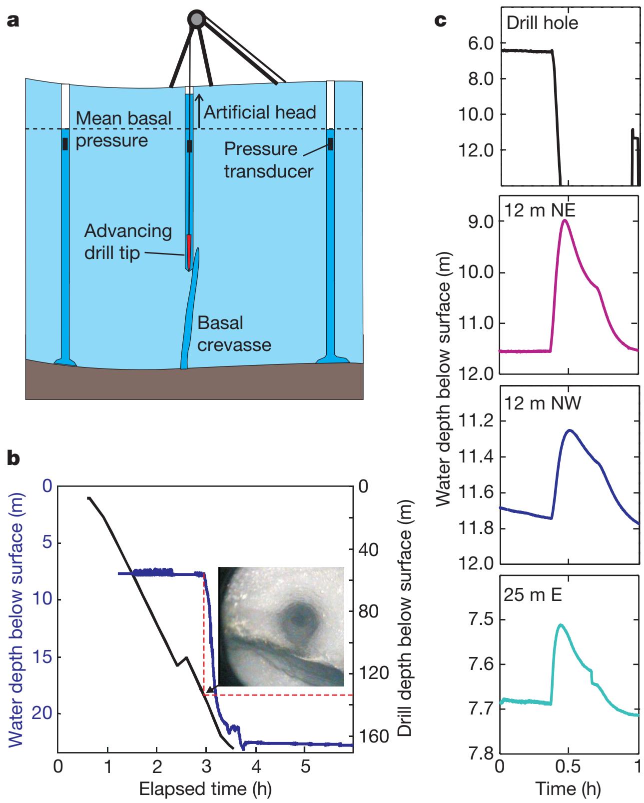

Figure 2 | Borehole drilling experiments. **a**, Overview showing hydraulic head in the drill hole relative to basal crevasses and adjacent boreholes. **b**, Borehole draining during a drilling experiment. Depths are referenced to ice surface. A crevasse was intersected at 133 m depth (32 m above the bed) as the drill tip advanced towards the bed (black line). The drill-hole water level (blue line) drained ~14 m upon intersection with the crevasse. The photograph inset shows the borehole video view looking down a 12-cm borehole (round, centre) and the intersecting crevasse. **c**, Separate experiment showing the response of adjacent holes to a drill hole intersecting with a crevasse. Holes are labelled with distance in metres and direction from drill hole. As the drill tip penetrated a crevasse at 102 m depth (61 m above the bed), the water level dropped more than 10 m in the drill hole while water levels in three holes up to 25 m from the drill hole simultaneously increased (note different vertical scales). Hole '25 m E' terminated ~10 m above the bed, and is interpreted to be connected to the bed via a separate basal crevasse observed by video.

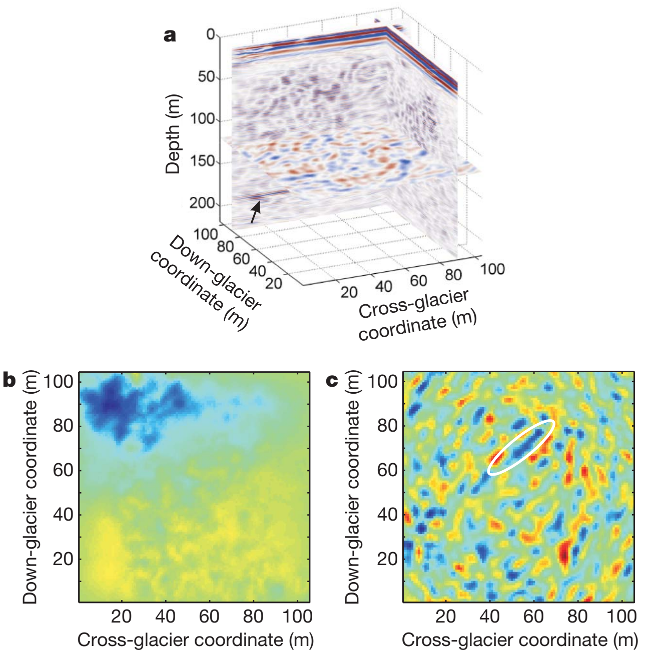

Figure 3 | 50-MHz 3D radar imaging of subsurface ice. Warmer colours represent more positive reflectivity and cooler colours represent more negative reflectivity. **a**, Slices through a data cube with 10,920 migrated radar traces in a 1.9×10^6 m^3 block of ice. Arrow shows bed at ~175 m ice depth. **b**, Horizontal slice at 16 m depth. Coherent scattering reflectors are noticeably absent, suggesting that water- or air-filled fractures are rare near the surface. **c**, Horizontal slice at 137 m depth (~38 m above the bed), showing numerous radar scattering events. Many events are laterally coherent over tens of metres (example shown by white ellipse) and have similar orientation to basal crevasses observed in the video. These events are interpreted as the tops of basal crevasses.

2.1% anisotropy with the fast direction oriented 16° from the flow line, which we interpret to result primarily from ice foliation. In the upper tens of metres of the ice mass, radar direct wave data show no measurable anisotropy, consistent with relatively unfractured shallow ice. In contrast, compressional waves and electromagnetic waves reflected from the bed show strong azimuthal velocity anisotropy at orientations of about 30° and 39° from the flow direction, respectively (Supplementary Fig. 5). This anisotropy is the expected result from water-filled planar sub-vertical fractures with preferred orientation throughout the study area.

We interpret englacial fractures with highly transmissive connections to the bed to be basal crevasses. The fractures are not likely to be hydro-fractures induced by our drilling, because we observed them where the density anomaly created by the water-filled borehole was insufficient to propagate a fracture to the bed, and because some fracture intersection events added water to the drill hole. Although the mechanical history of each fracture is uncertain, conditions were highly favourable for forming basal crevasses. Time-lapse video captured the opening of two fractures that appeared to propagate upward from the bed, implying that they were basal crevasses. For example, at a location 34 m above the bed of one borehole an approximately 15-cm aperture opened 11 days after the borehole was drilled (Supplementary Fig. 3). The new crevasse brought turbid water up from the bed, and also offset the borehole so that the camera could only be lowered into the crevasse. Finally, numerous basal crevasses are also implied by the similar orientation of steeply dipping crevasses observed by video and drilling experiments and the radar and seismic anisotropy.

To estimate water storage in basal crevasses we use the bulk water content of the ice measured by inversion of multi-channel, multi-offset georadar data (Supplementary Information, and Supplementary Fig. 6). These data suggest that water in macro-scale spaces occupies up to 1% of the ice mass over a distance of ~0.5 km along the flow-line and coincident with boreholes. We assume that crevasses in this area that are connected to the bed extend on average to 40 m above the bed. This assumption is based on drilling experiments and radar imaging and is conservative considering that drilling experiments identified multiple connected crevasses extending to 70 m. The water volume in 1% of the lower 40 m of the glacier equates to a 40 cm layer spread over the bed.

Borehole experiments provide a second and independent estimate of the water volume in hydraulically connected crevasses. Dividing the total intersected volume of all crevasses measured with video by the total volume of all boreholes implies that hydraulically connected crevasses occupy 0.3% of the ice mass below 50 m depth. For comparison, all englacial crevasses (connected and unconnected) occupy 0.46% of Worthington Glacier, Alaska[18], and all voids, channels and cracks combined occupy 1.3% of Storglaciären, Sweden[19]. Assuming crevasses extend 40 m above the bed, Bench Glacier's 0.3% value is equivalent to a 12 cm layer of water covering the bed. This is considerably less water than has been estimated by radar, probably reflecting differences in spatial sampling, errors in both methods, and the radar method's inclusion of closed-off voids and crevasses. Hence, on the basis of radar and borehole estimates, the volume of water in connected basal crevasses is (conservatively) a decimetre of water covering the bed. This is significant because we have observed a fivefold increase in the sliding speed of Bench Glacier associated with a 4 cm increase in bed separation that is due to water[20].

Previous work has focused on surface-to-bed water routeing through crevasses, either through rapid top-down crevasse propagation[21–23] or via slow laminar flow in established fractures[24]. Basal crevasses provide a storage mechanism distinctly different from previously described englacial fractures and conduits because they are not directly connected to surface water inputs. In comparison to subglacial cavities and conduits, basal crevasses do not necessarily form at similar locations with respect to bed roughness, and their storage capacity may not relate to water pressure or sliding velocity in the same way.

This suggests that our conceptual view of the basal drainage system as a 2D zone at the ice/bed interface should be modified to include the possibility of a 3D zone that extends tens of metres into the overlying ice.

The existence of basal crevasses has been inferred in vastly different glaciological settings[25–27]. Because high basal water pressure and extending flow favour basal crevasse formation, links between sliding speed and water storage in basal crevasses are possible. For example, elastic closure of crevasse walls could be a mechanism for maintaining high water pressure as cavities expand during sliding accelerations[20], thus enabling sustained hydraulic jacking. Basal crevasses could offer a source of water for winter surge initiation[28] and a sink for water when supraglacial lakes, such as those in Greenland, drain to the bed[22]. The subglacial drainage system is known to be spatially variable and often changes over timescales of hours to seasons. Filling and draining of basal crevasses could increase the dynamic nature of the drainage system, and could either buffer or catalyse feedbacks with sliding motion.

Our estimates of the water capacity of basal crevasses are for ~0.5 km of Bench Glacier, are based on simplifying assumptions, and cannot be transferred to all glaciers or even to Bench Glacier at all times of year. Nevertheless, our geophysical measurements indicate that a substantial volume of water can be stored in basal crevasses and our borehole experiments demonstrate that this water has a highly transmissive connection to the bed. These findings should be carefully considered as future field observations are interpreted and as new conceptual and numerical models of subglacial water flow are developed.

METHODS SUMMARY

Monitored drilling. Boreholes were hot-water drilled with the drill hole filled with water to near the ice surface during drilling. Water levels were measured at one-second intervals with up to six pressure transducers recorded by a single data logger. Pressure transducers were placed in the drill hole and adjacent boreholes 10–60 m away. The independently calibrated 10^5-Pa pressure transducers had resolution of about 10^{-3} m.

Seismic experiments. A 3D P-wave seismic reflection survey covered ~300 m × 300 m near the glacier centre line and had a 214-channel recording system arranged in a 105 m × 105 m chequerboard pattern (Fig. 1). The seismic source was a 7.26-kg manual jackhammer with flat plate and four hammer blows recorded at each station. We occupied 914 shot points with shooting geometry designed to ensure 90° of azimuthal coverage. Rayleigh waves were non-dispersive with estimated velocity uncertainty of less than 0.5%. Uncertainty in the reflection velocity analysis was less than 0.8%.

Radar experiments. 2D continuous multi-offset georadar surveys were conducted with a multichannel 25-MHz radar system along azimuths oriented at 0°, 45° and 90° relative to glacier flow and fifteen offsets between 5–150 m. We towed the radar system at 5–10 km per hour using a snowmachine with transmitter/receiver positions established using differentially corrected Global Positioning System (GPS; nominal 0.5 m trace spacing). The 3D radar survey used 50-MHz linear dipole antennas towed in a small sled and the antenna polarization aligned with glacier flow. We acquired 53 approximately parallel lines with a nominal cross-line spacing of 2 m, an in-line trace spacing of 0.5 m, and position control maintained using differential GPS. Data were interpolated onto a uniform grid using 3D Kirchhoff migration. Multi-azimuthal measurements were made by acquiring a 100 m° × 100 m multi-azimuthal, multi-offset 3D grid (Fig. 1).

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