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Paleofluvial and subglacial channel networks beneath Humboldt Glacier, Greenland

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ABSTRACT

The identification of subglacial drainage systems can inform our understanding of past and present hydrological processes, landscape evolution, and ice dynamics. Here, we present evidence from satellite imagery, digital elevation models, and radio-echo sounding data for a series of channelized networks with contrasting paleofluvial and subglacial origins beneath Humboldt Glacier, northern Greenland. A >250-km-long, dendritic paleofluvial channel network beneath the northern portion of Humboldt is interpreted as a preglacial feature. Roughly linear channels beneath the southern portion of Humboldt, which display a similar distribution to tunnel valleys found on the beds of former ice sheets, are likely to have been eroded by subglacial meltwater routed along the ice-sheet bed. We suggest that basal meltwater is actively being routed down both the paleofluvial and subglacially formed channel networks to the coast. Inheritance of the preglacial channel network may have influenced the present-day location and dynamics of Humboldt Glacier and enhanced selective erosion at its down-glacier end.

INTRODUCTION

Subglacial drainage systems modulate ice flow (Iken and Bindschadler, 1986) and the pattern of glacial erosion (Beaud et al., 2016). The seasonal evolution and distribution of channels cut into ice (Röthlisberger channels) and their influence on ice flow (e.g., Cowton et al., 2013) is well studied. But long-term (10^1 to 10^5 yr) drainage patterns and the persistency of subglacial channels remain poorly understood. Identifying whether channels incised into the bed originate from preglacial river erosion, subglacial erosion by water or ice, or turbidity flows in front of a marine-terminating glacier can inform our understanding of past and present hydrological processes, landscape evolution, and ice-sheet dynamics.

Roughly parallel subglacial channels carved by meltwater and up to several kilometers wide, tens of kilometers long, and tens to hundreds of meters deep (commonly termed tunnel valleys or channels) have been widely observed in formerly glaciated landscapes (Livingstone and Clark, 2016). Although several relict paleofluvial and subglacial channel networks have been identified beneath contemporary ice sheets (e.g., Bamber et al., 2013; Rose et al., 2014; Cooper et al., 2016), evidence for active meltwater drainage through large channels cut into the bed is limited.

Here we present satellite imagery and radio-echo sounding (RES) data, which reveal large channel networks of both paleofluvial and subglacial meltwater origin beneath Humboldt Glacier (~78–80°N, 65–59°W), an ~95-km-wide marine-terminating glacier that drains ~3% of the Greenland Ice Sheet (Rignot and Kanagaratnam, 2006) northwestward into the Nares Strait (Oakey and Damaske, 2006) (Fig. 1).

METHODS

We use the BedMachine digital elevation model (DEM; Morlighem et al., 2014) of subglacial topography to identify and map a series of roughly linear bed depressions orientated parallel to the present-day flow of Humboldt Glacier. The DEM uses a mass-conservation ice-sheet modeling approach, which combines RES surveys with ice velocity data and has a spatial resolution of 150 m (Morlighem et al., 2014). Channels were also identified from RES surveys of Humbolt Glacier conducted between A.D. 1999 and 2014 (Fig. 1A). Linear depressions that are visible in the DEM and RES data are interpreted as subglacial channels.

We analyzed repeat radar profiles from 2012 and 2014 to constrain basal properties from the RES bed-echo strength (e.g., Matsuoka et al., 2012; MacGregor et al., 2013), using high-relative-reflectivity anomalies as a qualitative indication for either a smoother bed or the presence of subglacial water (see the GSA Data Repository[1]) (Jacobel et al., 2009; Schroeder et al., 2016).

Brightness variations in the Moderate-Resolution Imaging Spectroradiometer (MODIS) Mosaic of Greenland (MOG) (Haran et al., 2015) were used to identify surface morphological features (Fig. 1B). As these variations largely reflect the transmission of subglacial topographic relief to the ice surface, mapped surface features provide additional independent information on subglacial topographic structures (Rose et al., 2014).

To assess the origin of the subglacial channels, we calculated hydrological pathways (Shreve, 1972) for both preglacial (ice-free) and present-day configurations (see the Data Repository) using the BedMachine DEM. The preglacial configuration was calculated by isostatically compensating the ice-free bed topography (after Bamber et al., 2013). For both preglacial and present-day configurations, we also predicted the route water may have taken before the channels formed by smoothing the bed DEM to remove the channels.

RESULTS

The DEM, MOG, and RES data reveal the presence of two distinct channel morphologies incised into subglacial topography beneath Humboldt Glacier (Figs. 1 and 2). The MOG data suggest that both sets of channels cut obliquely through southwest-northeast–orientated structures, interpreted as the continuation of offshore Proterozoic dikes (Oakey and Damaske, 2006; Fig. 1B).

Subglacial Valley Morphology

The northern, fast-flowing section of Humboldt Glacier (150–570 m a^{-1}; Joughin et al., 2010; Carr et al., 2015) comprises an up to 15-km-wide trough that deepens inland to >300 m below sea level and extends ~50 km inland of the ice margin (Fig. 1). The trough is fed by a dendritic and sinuous channel network that extends for 260 km. RES data show that these sinuous channels reach at least 400 m in depth and 7 km in width. Width-to-height ratios are typically <5, consistent with V-shaped channel morphologies, although some of the tributary channels further inland have more classical U-shaped valley profiles (width-to-height ratio of up to 20).

The southern, slower-flowing section of Humboldt Glacier (<150 m a^{-1}; Carr et al., 2015) is much shallower (maximum bed depth: 220 m below sea level), with a gentle bed slope, dipping northwards across ice flow. The bed is deeply

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[1]GSA Data Repository item 2017176, additional detail on the methodology involved in the investigation of basal properties from the radio echo sounding data and in the derivation of subglacial and preglacial drainage pathways, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

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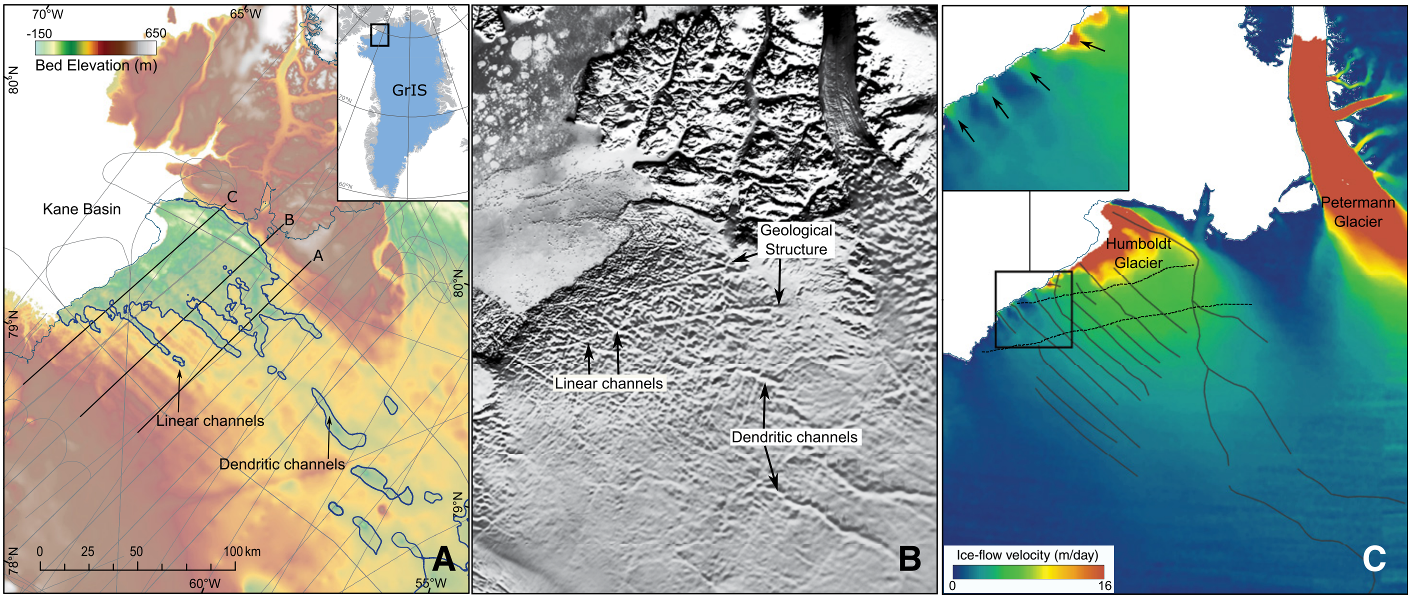

Figure 1. A: Mass-conservation bed digital elevation model (DEM) (Morlighem et al., 2014) of Humboldt Glacier, northern Greenland, and radio-echo sounding flight lines from A.D. 2012 and 2014 (thin gray lines), which were used to calculate potential water locations. Lines corresponding to radargrams in Figure 2 are in bold and were repeated in 2012 and 2014. Thick blue line is 0 m contour. GrIS—Greenland Ice Sheet. B: Moderate-Resolution Imaging Spectroradiometer (MODIS) Mosaic of Greenland (MOG) (Haran et al., 2015) of same area as in A, showing evidence of two southwest-northeast–trending, roughly linear forms, and southeast-northwest–trending sinuous forms that penetrate >100 km inland. C: Ice velocity structure of Humboldt Glacier catchment (MEaSUREs data; Joughin et al., 2010), with channels mapped from mass-conservation DEM (black lines) and geological structure mapped from MOG (dotted line) overlain. Note correspondence of mapped channels with higher relative ice-flow velocities within 15 km of margin (inset: arrows correspond to location of channels).

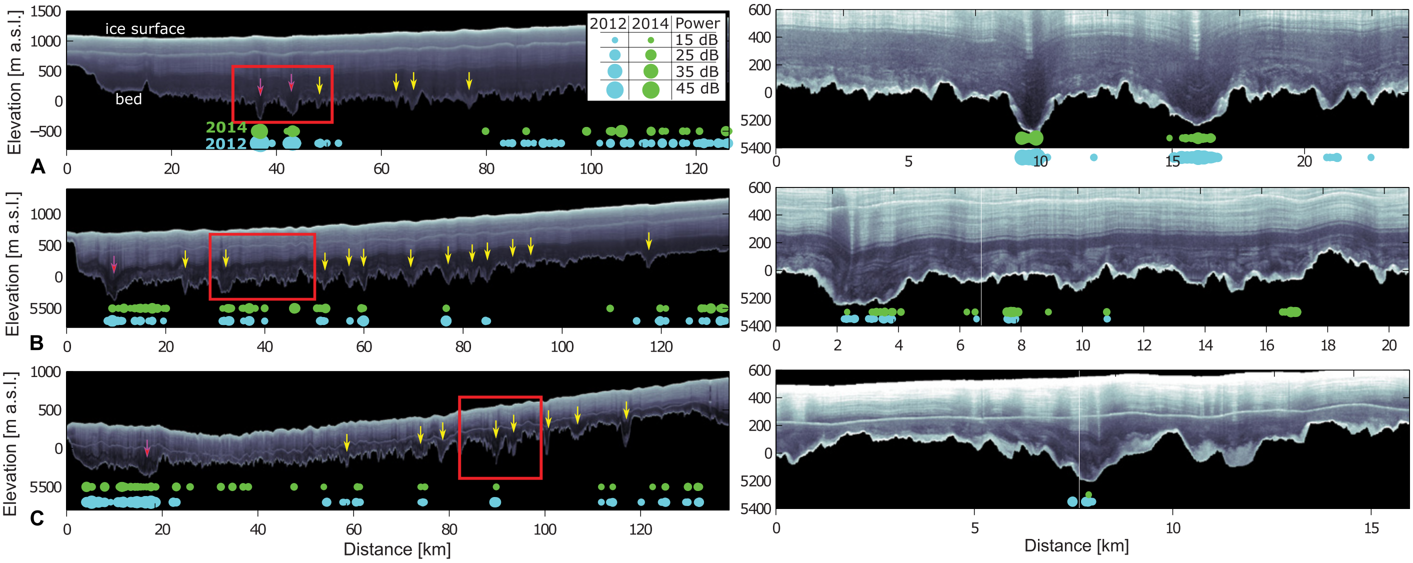

Figure 2. Ice-penetrating radargram profiles running across paleofluvial and subglacial channels at three locations, Humboldt Glacier, northern Greenland (shown in Figure 1 by solid black lines and corresponding letters). Blue and green dots refer to potential water locations calculated from radar profiles in A.D. 2012 and 2014, respectively. Pink arrows refer to paleofluvial channel network, and yellow arrows, linear subglacial channels. Right-hand panels present close-ups of channel morphology for each of the three radargrams (locations show by red boxes). m a.s.l.—meters above sea level.

incised by roughly linear channels orientated parallel to present-day ice flow and obliquely to the general bed slope (Figs. 1A and 2). These linear channels are up to 80 km in length and increase in size from 1.5–2.5 km wide and up to 325 m deep 65 km inland from the ice margin, where they are difficult to distinguish from the background bed roughness, to 2–4 km wide and up to 400 m deep 10 km from the ice margin. The channels are spaced at ~5 km intervals and are V-shaped with typical width-to-height ratios of <5. Within 15 km of the ice margin, the mapped channels are associated with appreciable (up to 3×) increases in ice-flow velocity (Fig. 1C).

Bed Reflectivity

In both the northern and southern regions of Humboldt Glacier, we interpret bed reflectivities ≥15 dB above the mean to indicate either subglacial water or a smooth bed (Fig. 2) (Oswald and Gogineni, 2008; Schroeder et al., 2016). Large regions of the northern sector of

Humboldt Glacier, in the overdeepened trough and along the base of the dendritic channel network, have bright reflections in both the 2012 and 2014 profiles. In the southern sector, bright reflections tend to occur along the base of the linear channels and be persistent over time, but this pattern is not consistent across all the channels. There is a clear contrast between regions with channelized bed topography, where bright reflections are restricted to the deeply incised channels, and smoother regions, such as on the trough floor at the northern margin of Humboldt Glacier, where bright reflections are more continuous (e.g., Oswald and Gogineni, 2012).

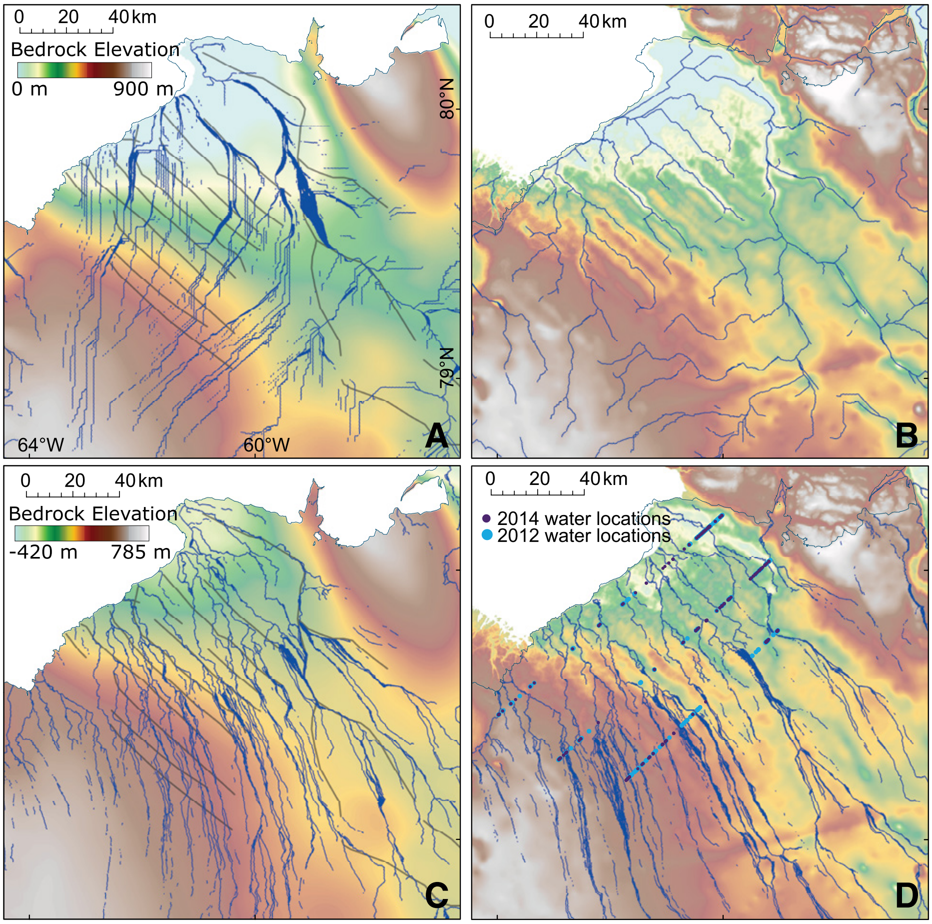

Figure 3. Preglacial and subglacial hydrological pathways (blue lines) (see Data Repository [see footnote 1]), Humboldt Glacier, northern Greenland. A: Preglacial configuration with isostatically compensated bed and with channels smoothed out. B: Preglacial configuration with isostatically compensated bed. Elevation scale is same as in A. C: Present-day ice and bed configuration with channels smoothed out. D: Present-day ice and bed configuration. Elevation scale is same as in C. Potential water locations derived from high-bed-reflectivity anomalies that are at least 15 dB greater than mean are shown for overlapping flight lines from A.D. 2012 and 2014. Mapped channels from Figure 1C are included in panels A and C (thick gray lines).

DISCUSSION

Channel Formation

We interpret the dendritic and sinuous channel network beneath the northern section of Humboldt Glacier as an inherited fluvial landscape of preglacial origin. The V-shaped channel cross-profiles imply that fluvial incision was the primary channel-forming process, while the curvilinear, dendritic planform is similar to subaerial river networks. This configuration is comparable with other paleofluvial landscapes identified beneath the Greenland Ice Sheet, including a mega-canyon that drains into the neighboring Petermann Glacier (Bamber et al., 2013) and the Jakobshavn Isbræ drainage catchment in southwestern Greenland (Cooper et al., 2016). Hydraulic potential calculations for the isostatically compensated and smoothed preglacial bed topography show how the dendritic river network can be reproduced without the presence of an ice sheet (Fig. 3A). At the down-glacier end of the channel network there is a large overdeepened trough, which we attribute to subsequent modification by glacial erosion (Cook and Swift, 2012). This enhanced, selective erosion is likely a consequence of concentrated glacier sliding. Further inland, where ice flow is slower, the inherited preglacial network pattern is largely preserved, although variations in valley morphology (V- to U-shapes) imply some selective glacial erosion.

The series of linear channels beneath the southern section of Humboldt Glacier is interpreted to have formed subglacially by meltwater erosion. Evidence includes their parallel arrangement and orientation oblique to the major slope direction and parallel to ice flow (Figs. 1A and 2), which is typical of subglacial meltwater drainage driven by ice overburden pressure (Shreve, 1972). Hydraulic potential calculations demonstrate how the subglacial channel configuration can be roughly reproduced using the present-day ice configuration and with the channels removed from the bed topography (Fig. 3C). However, there is still some misalignment, particularly to the south of the study area, which suggests that initial formation of the subglacial channels was likely associated with a more extensive ice-sheet configuration. The formation of large subglacial channels running oblique to the preglacial drainage pattern (Fig. 3A) demonstrates the efficacy of subglacial fluvial erosion in landscape evolution.

The dimensions, morphology, spacing, and arrangement of the channels are analogous to those of bedrock and sediment eroded tunnel valleys observed in paleo-landscapes in both marine and terrestrial settings, suggesting a commonality of process (e.g., Lowe and Anderson, 2003; Livingstone and Clark, 2016). The rough bed (Fig. 2) and geological structure evident in the MOG data (Fig. 1B) allow us to speculate that bedrock lies close to or at the ice-bed interface, and therefore that the channels beneath Humboldt are cut, at least partially, into bedrock.

Subglacial Drainage

The bed echoes from the 2012 and 2014 RES survey lines suggest either a smoother bed (e.g., sediment floored) or the presence of water in the paleofluvial channel network and many of the subglacially formed channels. The latter interpretation is consistent with hydraulic potential calculations (Fig. 3D), which suggest that meltwater drainage beneath the present ice sheet is actively being routed down many of the large channels.

Basal water is sourced from surface runoff draining to the bed via moulins and from basal melt due to frictional heating and geothermal heat. Extensive portions of northern Greenland, including the Humboldt Glacier catchment, have a basal temperature equal to the pressure-melting temperature (Oswald and Gogineni, 2012; MacGregor et al., 2016). These warm bed conditions associated with the Humboldt catchment are modeled to extend >100 km inland and originate from a geothermal anomaly (Rogozhina et al., 2016). Thus, the long-term and large-scale pattern of subglacial channel incision under Humboldt Glacier is consistent with the regional tectonothermal history of northern Greenland (Rogozhina et al., 2016). Moreover, frictional melting is likely to be significant beneath the fast-flowing northern portion of Humboldt Glacier, while surface water draining to the bed in the ablation zone may provide a significant portion of the present-day basal meltwater flux. This is supported by the presence of supraglacial lakes up to ~70 km inland of the ice margin (Selmes et al., 2011).

Ice Dynamics

Paleofluvial valley networks beneath the Greenland Ice Sheet are typically associated with fast-flowing outlet glaciers (Bamber et al., 2013; Cooper et al., 2016). Thus, large preglacial drainage networks may have acted as seed points for the inception of fast-flowing outlet glaciers due to the convergence of ice and water down the dendritic catchments (see also Cooper et al., 2016). Although there is locally increased ice flow focused along the subglacially formed channels near the ice margin, regional ice velocities are generally much slower along the southern portion of Humboldt Glacier (Fig. 1C). This could be a result of: (1) the linear subglacial drainage network inhibiting convergent ice and water flow; (2) the different topographic settings, i.e., preglacial drainage networks tend to form in large basins where ice will be thick, while subglacial channel networks are less influenced by topography so can occur under thinner, slower-moving ice; and/or (3) focused water drainage along the linear subglacial channels causing sticky inter-channel ridges with higher basal traction.

CONCLUSIONS

Using satellite imagery, bed DEMs, and RES data, we identified an extensive series of deeply incised (up to 400 m) channels at the bed of Humboldt Glacier, northern Greenland, which provide information on how ice sheets exploit and modify landscapes through subglacial fluvial processes. Roughly linear channels at the southern end of Humboldt are envisaged to have been eroded by subglacial meltwater, while the >250-km-long dendritic channel system at the fast-flowing northern section of Humboldt Glacier is interpreted as a paleofluvial network inherited from a preglacial landscape. We suggest that the location and flow of the present-day Humboldt Glacier is controlled by the inherited paleofluvial landscape, similar to other fast-flowing outlet glaciers around Greenland. Bed reflectivity anomalies and hydraulic potential calculations are consistent with active meltwater drainage down both channel networks. The subglacial channels represent a useful analogue for understanding tunnel valleys and channels found on the bed of paleo–ice sheets.

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