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RESEARCH LETTER

Paleofluvial landscape inheritance for Jakobshavn Isbræ catchment, Greenland

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Abstract Subglacial topography exerts strong controls on glacier dynamics, influencing the orientation and velocity of ice flow, as well as modulating the distribution of basal waters and sediment. Bed geometry can also provide a long-term record of geomorphic processes, allowing insight into landscape evolution, the origin of which may predate ice sheet inception. Here we present evidence from ice-penetrating radar data for a large dendritic drainage network, radiating inland from Jakobshavn Isbræ, Greenland's largest outlet glacier. The size of the drainage basin is ~450,000 km^2 and accounts for about 20% of the total land area of Greenland. Topographic and basin morphometric analyses of an isostatically uplifted (ice-free) bedrock topography suggests that this catchment predates ice sheet initiation and has likely been instrumental in controlling the location and form of the Jakobshavn ice stream, and ice flow from the deep interior to the margin, now and over several glacial cycles.

1. Introduction

Recent efforts to characterize ice thickness and subglacial bed elevations of large ice masses have involved detailed, and repeated, geophysical surveys using ice-penetrating radar (IPR) over Antarctica and Greenland (often referred to also as radio-echo sounding) [e.g., *Bamber et al.*, 2001, 2013a; *Fretwell et al.*, 2013]. Such data provide a rich source of information that can be used to explore landscape origin and evolution [e.g., *Young et al.*, 2011], as well as hydrological processes [e.g., *Wright et al.*, 2008]. Quantifying attributes of subglacial morphology and landscape origin can provide insights into past and present erosional regimes, ice sheet development and former patterns of ice flow [*Siegert et al.*, 2005; *Bingham and Siegert*, 2009; *Rose et al.*, 2013], the distribution of basal water, and ancient subglacial hydrological pathways [*Baroni et al.*, 2005; *Rose et al.*, 2014; *Jamieson et al.*, 2016].

Morphological studies have shown relict "preglacial" landforms preserved at the beds of former ice sheets, surviving successive periods of glaciation [e.g., *Kleman*, 1994; *Kleman and Hättestrand*, 1999; *Hall et al.*, 2013]. These have raised discussions on the efficiency of glacial erosion and "erasure," as well as on the glacial and geological conditions that facilitate landscape preservation beneath ice sheets [*Sugden and John*, 1976; *Kleman*, 1994; *Koppes and Montgomery*, 2009]. Crucially, the effects of ice sheet erosion will be superimposed onto the preglacial topography [*Sugden*, 1974], presenting a palimpsest of geomorphic origin and landscape evolution. The nature of these landscapes and, as such the "type" of glacial erosion, is often distinct [e.g., *Sugden*, 1974]. Regions marked by evidence of "selective linear erosion" are characterized by landscape preservation directly adjacent to areas of intense erosion, due to the interplay of preexisting basal topography and geometry, rock type, and basal thermal regime [*Sugden*, 1974; *Sugden and John*, 1976; *Drewry*, 1986]. In the case of ice sheet inception over preglacial fluvial surfaces, selective linear erosion will act to deepen river valleys, while preserving the spatial pattern of the channels.

The geological setting and glacial history of Greenland yield conditions amenable to the long-term conservation of subglacial landscapes. The island is dominated by Precambrian crystalline, gneissic shield rocks with limited sedimentary deposits [*Henriksen*, 2008; *Henriksen et al.*, 2009], and has only been extensively ice covered for about the last 3.5 million years (Ma) [*Kleiven et al.*, 2002; *Alley et al.*, 2010]. To date, most analysis of subglacial geomorphology, and basal landscape origin, has been focused on Antarctica (e.g., the "Ellsworth Subglacial Highlands" [*Ross et al.*, 2014] and "preglacial erosional (planation) surfaces" of the West Antarctic Ice Sheet [*Rose et al.*, 2015]), with little focus on such associations in Greenland. However, a large subglacial "megacanyon" in northern Greenland, thought to be of paleofluvial origin, has recently been discovered [*Bamber et al.*, 2013b], allowing new insights into Greenland's landscape history and past processes of
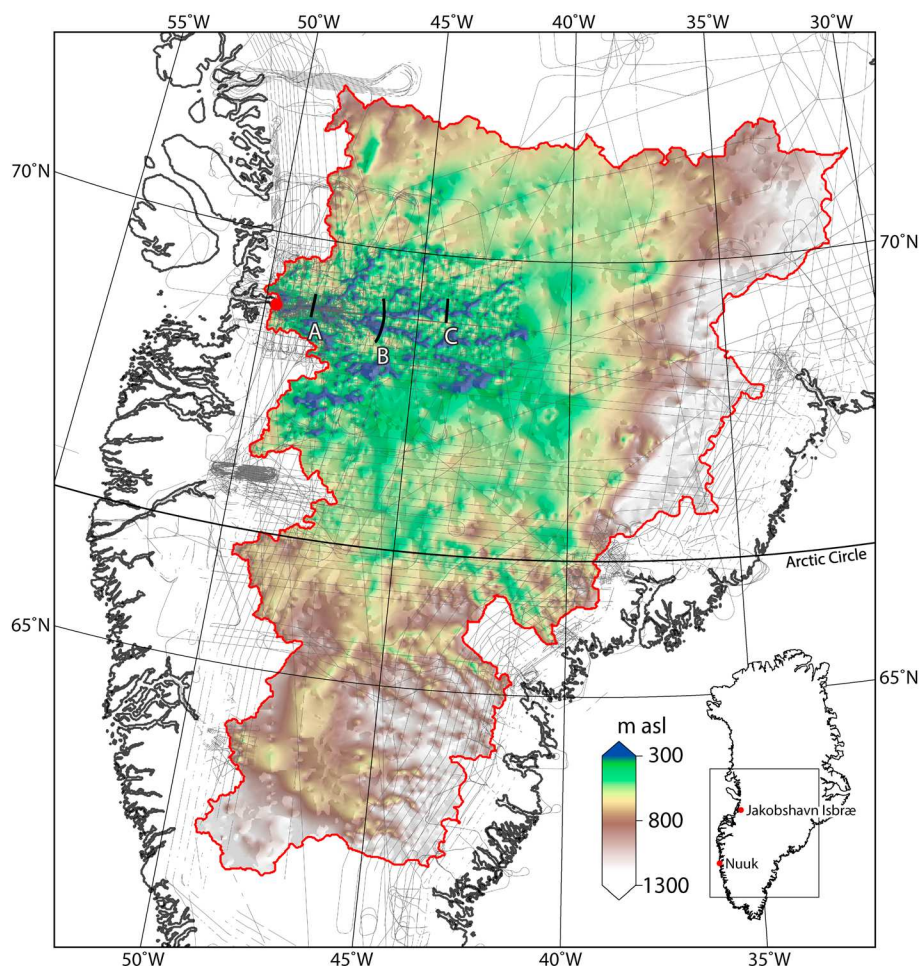
Figure 1. Bed elevation (between 300 and 1300 m above sea level (asl)) for southern Greenland, and the wider Jakobshavn Isbræ area. The area plotted is indicated by the black box in the inset. The calculated water divide of the Jakobshavn Isbræ hydrographic basin is delineated in red. Airborne ice-penetrating radar flight lines (collected between 2006 and 2014) are shown in gray, and three bed profiles (A–C) plotted in Figure 3 are shown by the respective solid lines.

landscape evolution. Despite several decades of airborne geophysical surveys, providing accurate and detailed bed topography for Greenland [*Bamber et al.*, 2013a], studies of the long-term subglacial landscape evolution, and the effects of topography on both subsequent glaciation and contemporary ice dynamics, have been limited.

In this paper, we use IPR and derived data to measure and analyze the subglacial morphology of southern Greenland and, from this, present evidence for an extensive drainage basin of paleofluvial origin, directly beneath a major glacial outflow unit. Further, we consider the impact this topography has on past and contemporary ice dynamics (namely, flow velocity and orientation), revealing the importance of landscape inheritance on ice sheet evolution.

2. Calculating Land Surface Water Flow Paths

Topographic analyses and hydrologic basin calculations were conducted on an isostatically compensated digital elevation model (DEM) of Greenland, presented by *Bamber et al.* [2013b], referred to hereafter as the "iDEM." The initial bed elevation for this iDEM was derived from a combination of extensive IPR ice thickness surveys and satellite-derived surface altimetry and was compiled at a 1 km posting resolution [*Bamber et al.*, 2013a]. The iDEM accounts for a flexural rebound of the bed, following the removal of the modern ice sheet load, and yields a configuration of bed topography that closely represents preglacial elevation. It is important to note that the preglacial morphology of Greenland cannot be recreated, and the iDEM studied
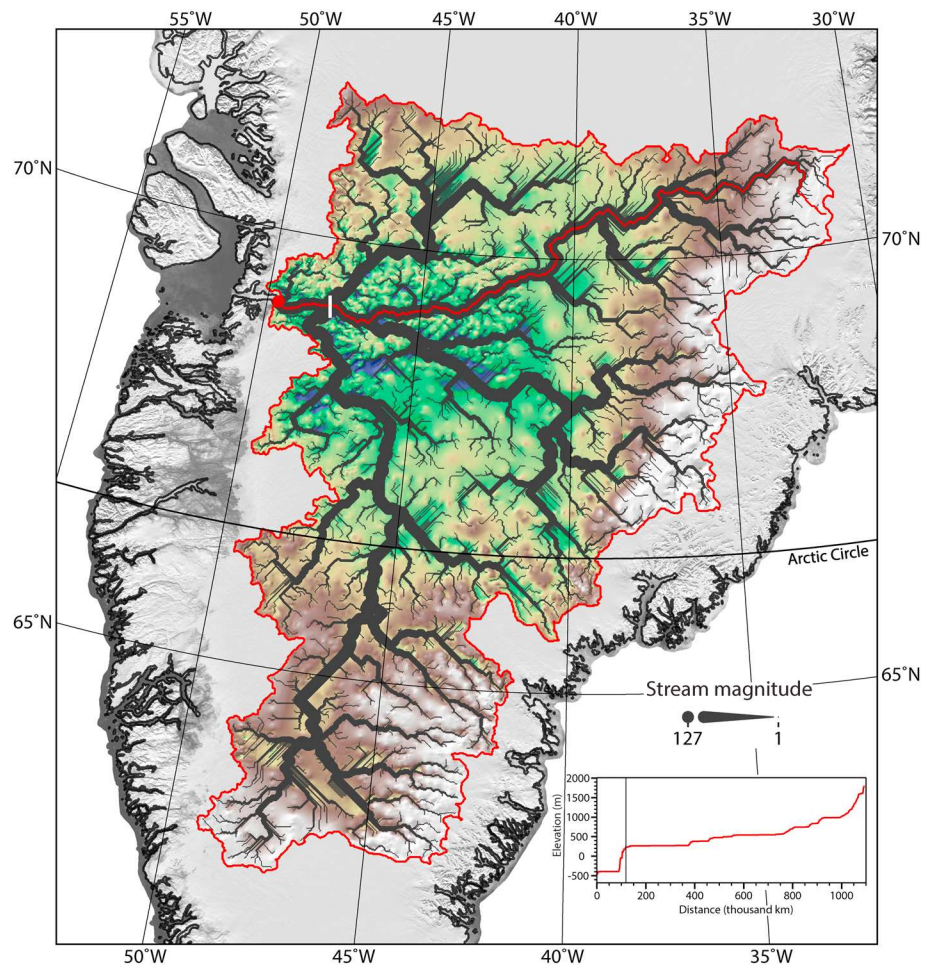
Figure 2. Flow routing network and Shreve [*Shreve*, 1966] stream magnitude for the paleofluvial Jakobshavn Isbræ basin. A main stream of the catchment is marked by the solid red line, with its longitudinal profile inset. A downstream knickpoint of this channel is marked by the solid white and black lines on the main and inset figures, respectively.

here assumes a landscape not significantly altered by the ice sheet since its inception. This assumption is supported by the fact that glacial erosion is largely selective, and the flow of ice is constrained by preexisting topography [*Sugden and John*, 1976; *Summerfield*, 1991]. The iDEM facilitates the identification of large-scale landform features, and their analysis, to determine predominant erosional processes and landscape origin.

The iDEM of southern Greenland displays a dendritic network of valleys, radiating inland from Jakobshavn Isbræ, Greenland's largest outlet glacier [*Echelmeyer and Clarke*, 1991] (Figure 1). Due to the nature of the IPR coverage across the island [*Bamber et al.*, 2013a], the ability to resolve topography in this region degrades at about 300 km inland from the coast, coinciding with more sparse flight line coverage (see Figure 1). Errors in bed elevation are primarily a function of distance from flight lines [see *Bamber et al.*, 2013a]. IPR observations remain relatively "dense" throughout the majority of the basin, particularly in the south and immediately surrounding Jakobshavn Isbræ, with the eastern and northeastern limits being more sparsely sampled. Here dense regions are defined as areas with greater than 1000 ice thickness measurements within a 50 km radius. Full details of the accuracy and uncertainties of this data set are given in *Bamber et al.* [2013a].

In order to ascertain the geomorphic origin of this region and to determine the potential influence of preglacial surface waters on the landscape and thus the flow of ice, topographic and morphometric analyses were undertaken. Initially, hydrographic basins and flow routing networks were calculated for the region using two separate software packages (SAGA-GIS [*Conrad and Olaya*, 2004; *Böhner and Conrad*, 2007] and Land Surface Dynamics Topography Tool Box (LSDTopoToolBox) [*Mudd et al.*, 2013]) in order to test the robustness of the resultant basin. "Sinks" within the iDEM were filled prior to calculation, a general step used in hydrological
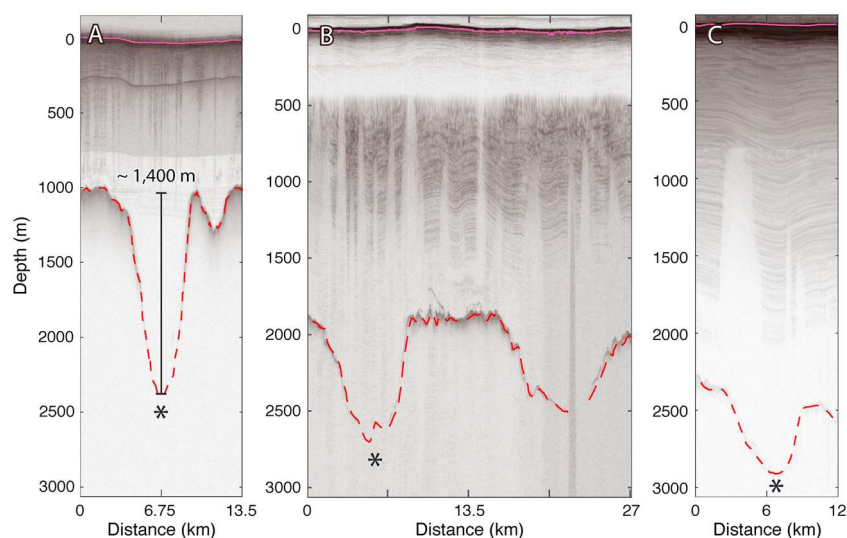
Figure 3. Ice-penetrating radargram profiles across the flow network at three locations (a-c). These locations are indicated in Figure 1 by A–C (solid black lines). There is an exaggeration in the vertical by a factor of 13. The bed return has been picked, the dashed red line, showing bedrock depth relative to the ice surface, the solid purple line. Cross sections of the main channel, as seen in Figure 2 (solid red line), are marked with the asterisk.

analysis to remove any topographic lows in the DEM which prevent discontinuities in calculated flow paths, and the subsequent network. The drainage network was extracted from the interior to the present-day coast-line based on a steepest-descent algorithm. The difference in area of the drainage basins between the two approaches was not significant, providing confidence that the depiction of the drainage system is robust. The total areas varied by ~62,000 km^2 (~10%). Furthermore, the network structure and watershed boundary of both basin calculations were nearly identical (see Figure S1 in the supporting information), with only a slight difference in the northwestern corner where IPR track spacing is most sparse. The smaller of the two basins (delineated in Figures 1 and S1) was used for subsequent analysis.

3. Network Characteristics

Figures 1 and 2 present the calculated drainage basin for the catchment incorporating Jakobshavn Isbræ and its flow routing network, respectively. The calculated basin size is 442,584 km^2, comparable with the Ohio River basin, USA, and accounts for about 20% of the total land area of Greenland. Much of the basin is relatively low-lying and smooth (Figure 1; with low relief, an average elevation ~748 m and slope of 0.8°); however, the eastern limit gives rise to a more mountainous, high-elevation terrain, as a result of the Caledonian fold belt (formed ~420 Ma B.P.) [Henriksen, 2008]. The relief (elevation range) of the basin is 3382 m, with a minimum elevation at the outlet, of ~458 m below sea level.

Figure 2 shows Shreve's [Shreve, 1966] stream magnitude (number of upstream unbranched streams) calcu-lated for the basin, presenting a metric for basin scale and network arrangement. The dendritic and sinuous nature of the calculated flow routing (Figure 2), as well as magnitude and tributary hierarchy, suggests that the hydrological system may have once been a viable drainage network prior to the inception of the ice sheet. In addition to analysis of the structure of the calculated flow paths, channel and basin morphology (long-profile and cross-section geometry) was considered with regard to their geomorphic process origin and erosion rates.

Figure 3 shows airborne IPR profiles at three points along the calculated channel network. Figure 3a was taken nearest the outlet (the topographic low point along the basin boundary), through which the entire network drains, coincident with the present-day Jakobshavn Isbræ; Figures 3b and 3c present cross sections upstream from this point, documenting some of the main channels of this dendritic system. The IPR data indicate that the channels are very large with a relative depth up to about 1400 m and a width of ~12 km; dimensions that exceed parts of the north Greenland megacanyon, reported previously by Bamber et al. [2013b].
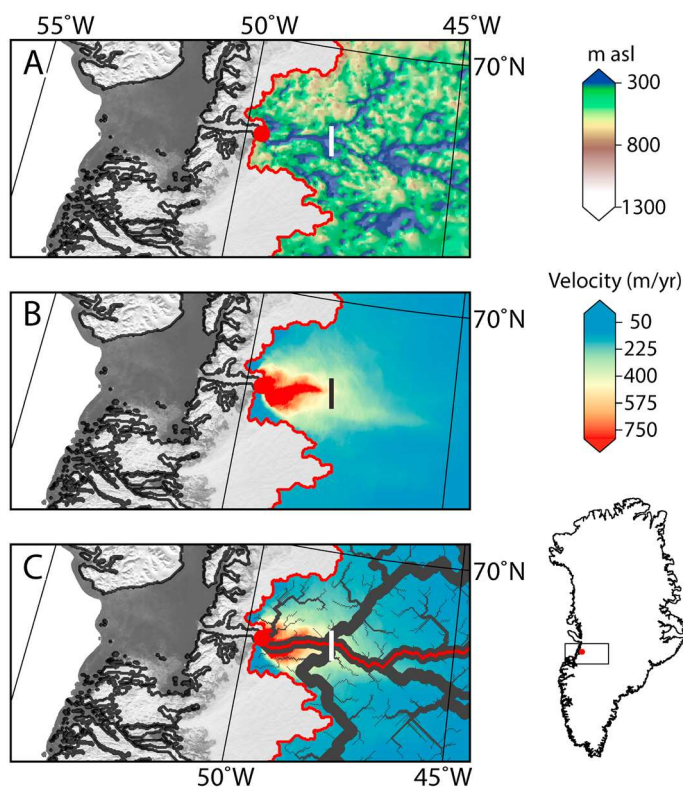
Figure 4. Influence of subglacial topography, and paleofluvial network, on contemporary ice dynamics at the basin outlet, Jakobshavn Isbræ. (a) iDEM, as Figure 1, omitting flightlines; (b) 2008/2009 MEaSUREs surface ice velocity [*Joughin et al.*, 2010]; (c) as in Figure 4b but with flow routing network from Figure 2 overlaid with line weight decreased by half. The solid white and black cutlines mark the location of the longitudinal knickpoint shown in Figure 2. Surface velocity of Jakobshavn Isbræ at the outlet exceeds $10 \, \text{km a}^{-1}$.

Channel cross-section geometry and calculation of valley width-to-depth ratios are used to differentiate between U- and V-shaped valleys and, therefore, between predominantly glaciated (i.e., glacially (re)modified) and solely fluvially incised geometries, respectively [*Graf*, 1970; *Bull and McFadden*, 1977]. The ratio for the channels shown in Figure 3 range from between 1.2 and 8.89, indicating that fluvial incision has been the dominant channel-forming process. Higher ratios, whereby a channel is relatively broad and shallow, are more characteristic of glacially worked channels, with those solely from glacial erosion having lower incision rates [*Graf*, 1970].

The longitudinal profile of one of the main channels is concave up and involves a series of steps and flats. At the headwaters, the profile shows a relatively sharp change in gradient from the Caledonian mountain region. This morphology is indicative of headwater streams, documenting high rates of incision and low sinuosity. As the channel continues downstream toward lower elevations, the long profile becomes relatively smooth, reflecting the nature of a broadening and graded fluvial system. The long profile terminates following a large "knickpoint" (an abrupt break in slope) (Figure 2; black and white solid lines), coincident with the confluence of three channels (see Figures 1, 2, and 4c) and fast glacial flow ($>750 \, \text{m a}^{-1}$ [*Joughin et al.*, 2010]; see Figure 4b).

4. Discussion

The topographic and morphometric analyses undertaken for the Jakobshavn Isbræ region largely point toward an inherited fluvial landscape of a preglacial (prior to extensive glaciation) origin. The calculated hydrologic basin and drainage network are seen to be well developed and extensive, with both a dendritic and sinuous structure (Figure 2). The concave up long profile presented is typical of fluvial networks, and V-shaped valley bottom geometries are suggestive of a dominant signal of fluvial incision. While the

underlying topography will have been subject to glacial erosion, the influence of a slow-flowing and cold-based interior in this region, owed partly to divergent flow and ice divides [*Sugden and John*, 1976; *Drewry*, 1986], will have led to minimal glacial erosion and incision throughout much of the basin.

It is widely documented that under certain glacial and geological conditions, landforms are able to be left largely unmodified by subsequent glaciation and erosion, particularly, in the case of larger, more "robust" features [*Kleman*, 1994]. Our analysis reveals that the Greenland ice sheet has modified the landscape only in a highly selective manner, as constrained by the preexisting topography [*Sugden*, 1974; *Sugden and John*, 1976]. Modification, through glacial erosion, will be enhanced in hydrologically active portions of the ice sheet (where surface meltwater is able to access the bed), as well as in regions of altered (warmer) basal thermal regime, increased ice velocity, and ice thickness [*Sugden*, 1974; *Sugden and John*, 1976; *Drewry*, 1986], characteristics that are largely influenced by large-scale basal topography. The observed knickpoint toward the basin outlet (Figure 2 (inset)) is a likely candidate for such enhanced selective erosion following the onset of glaciation, excavating further a valley formed by the action of preglacial fluvial activity. Figure 4 documents a coincident ice convergence zone and increase in ice surface velocity. Lateral convergence of ice gives rise to enhanced glacial erosion rates [*Sugden*, 1974; *Sugden and John*, 1976; *Drewry*, 1986], which can lead to the formation of a "glacial stairway" (stepped long profiles), as documented in numerous valley glacier systems [*Anderson et al.*, 2006]. Such a feature is observed throughout the long profile documented here (Figure 2, inset). Glacial overdeepening is also present at other confluences in the subglacial channel network (see Figures S2 and S3), further confirming an erosive signal of the ice sheet superimposed upon the preglacial fluvial landscape, through selective means.

Aside from the geomorphic impact of the Greenland ice sheet upon the underlying topography, it is also important to consider the controls of bed geometry on ice dynamics. Figure 4 shows surface ice velocity for 2008/2009 (MEaSUREs) [*Joughin et al.*, 2010] for Jakobshavn Isbræ alongside bed elevation. Surface velocity increases by many orders of magnitude toward the outlet, following the observed knickpoint in the longitudinal profile (Figures 2 and 4 (solid white and black lines)), and confluence of major subglacial channels; increases in surface velocity are also documented to fork upstream, mapping the underlying subglacial channels (Figures 4b and 4c). While these increases are perhaps unsurprising, owing to ice convergence and increased ice thickness (as ice velocity is proportional to the fourth power of ice thickness [*Cuffey and Paterson*, 2010]), it is remarkable to consider that the ancient bed topography has such a marked influence on the location of surface velocities and ice dynamics, where the flow of ice itself is usually seen as an important control upon bedrock topography from an erosional standpoint. It is reasonable to assume that a similar arrangement between ice flow and topography existed previously; hence, the fluvial system documented here is likely to have affected the flow of the Greenland ice sheet since its inception, at least in the study area presented here.

5. Conclusions

We have presented a detailed study on the subglacial geomorphology of southern Greenland and, through topographic and morphometric analysis, documented evidence for a large-scale drainage basin of likely paleofluvial origin. We believe the delineated basin and flow routing network to be robust, and while track spacing is variable across the region, the error for the majority of catchment is <125 m [*Bamber et al.*, 2013a]. Where the track spacing is more sparse, the topography is generally smoother (the island's interior) and a more coarse and interpolated measurement is seen as adequate [*Bamber et al.*, 2013a].

While this region has been subject to glacial erosion throughout the history of the GrIS, the preexisting fluvial landscape, made evident by the dendritic nature of the system and V-shaped valley bottoms, is likely to have led to subsequent processes of selective glacial erosion. These processes have since modified the dimensions of parts of the basin, most notably toward the basin outlet, through a long-term process of landscape evolution. The ancient bed topography presents, through landscape inheritance, a defining influence on the modern ice sheet configuration and contemporary dynamics, constraining the flow of ice, helping to explain the location, size, and velocity of the Jakobshavn Isbræ ice stream, Greenland's largest outlet glacier. It stands to reason that former ice cover in Greenland has been similarly influenced.

This paper has opened discussion on this region and landscape, providing the first interpretation of Greenland's underlying topography with respect to the established literature on the selective nature of

glacial erosion, and landscape inheritance [e.g., *Hall et al.*, 2013; *Sugden*, 1974; *Sugden and John*, 1976]. This work allows future interpretation into the two-way relationship between ice sheet glacial erosion and preexisting topography, as well as providing new information to understanding long-term landscape evolution. Further, it adds to the growing collection of research on preglacial landscape inheritance both in Greenland and Antarctica.

References

Alley, R. B., et al. (2010), History of the Greenland ice sheet: Paleoclimatic insights, *Quat. Sci. Rev.*, *29*(15–16), 1728–1756, doi:10.1016/j.quascirev.2010.02.007.

Anderson, R. S., P. Molnar, and M. A. Kessler (2006), Features of glacial valley profiles simply explained, *J. Geophys. Res.*, *111*, F01004, doi:10.1029/2005JF000344.

Bamber, J. L., R. L. Layberry, and S. P. Gogineni (2001), A new ice thickness and bed data set for the Greenland ice sheet: 1. Measurement, data reduction, and errors, *J. Geophys. Res.*, *106*(D24), 33,773–33,780, doi:10.1029/2001JD900054.

Bamber, J. L., et al. (2013a), A new bed elevation dataset for Greenland, *Cryosphere*, *7*(2), 499–510, doi:10.5194/tc-7-499-2013.

Bamber, J. L., M. J. Siegert, J. A. Griggs, S. J. Marshall, and G. Spada (2013b), Paleofluvial mega-canyon beneath the central Greenland ice sheet, *Science*, *341*(6149), 997–999, doi:10.1126/science.1239794.

Baroni, C., V. Noti, S. Ciccacci, G. Righini, and M. C. Salvatore (2005), Fluvial origin of the valley system in northern Victoria Land (Antarctica) from quantitative geomorphic analysis, *Geol. Soc. Am. Bull.*, *117*(1–2), 212–228, doi:10.1130/B25529.1.

Bingham, R. G., and M. J. Siegert (2009), Quantifying subglacial bed roughness in Antarctica: Implications for ice-sheet dynamics and history, *Quat. Sci. Rev.*, *28*(3–4), 223–236, doi:10.1016/j.quascirev.2008.10.014.

Böhner, J., and O. Conrad (2007), SAGA-GIS.

Bull, W. B., and L. D. McFadden (1977), Tectonic geomorphology north and south of the Garlock fault, California, in geomorphology in arid regions, in *A Proceedings Volume of the Eighth Annual Geomorphology Symposium Held at the State University of New York at Binghamton, September 23–24, 1977*, Proceedings of the eighth annual geomorphology symposium. State University of New York, Binghamton, edited by D. O. Doehring, pp. 115–138, George Allen & Unwin, Binghamton.

Conrad, O., and V. Olaya (2004), SAGA-GIS: Terrain analysis–hydrology.

Cuffey, K. M., and W. S. B. Paterson (2010), *The Physics of Glaciers*, Academic Press, London.

Drewry, D. J. (1986), *Glacial Geologic Processes*, E. Arnold, London.

Echelmeyer, K., and T. S. Clarke (1991), Surficial glaciology of Jakobshavns Isbræ, West Greenland: Part I. Surface morphology, *J. Glaciol.*, *37*, 368–382.

Fretwell, P., et al. (2013), Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica, *Cryosphere*, *7*(1), 375–393, doi:10.5194/tc-7-375-2013.

Graf, W. L. (1970), The geomorphology of the glacial valley cross section, *Arct. Alp. Res.*, *2*(4), 303–312.

Hall, A. M., K. Ebert, and C. Hättestrand (2013), Pre-glacial landform inheritance in a glaciated shield landscape, *Geogr. Ann., Ser. A*, *95*(1), 33–49, doi:10.1111/j.1468-0459.2012.00477.x.

Henriksen, N. (2008), *Geological History of Greenland. Four Billion Years of Earth Evolution*, 1st ed., Geological Survey of Denmark and Greenland (GEUS).

Henriksen, N., A. Higgins, F. Kalsbeek, and T. C. R. Pulvertaft (2009), Greenland from Archaean to Quarternary–Descriptive text to the 1995 geological map of Greenland, 1:2,500,000. 2nd edition, *Geol. Surv. Den. Greenl. Bull.*, *18*, 1–126.

Jamieson, S. S. R., N. Ross, J. S. Greenbaum, D. A. Young, A. R. A. Aitken, J. L. Roberts, D. D. Blankenship, S. Bo, and M. J. Siegert (2016), An extensive subglacial lake and canyon system in Princess Elizabeth Land, East Antarctica, *Geology*, *44*(2), 87–90, doi:10.1130/G37220.1.

Joughin, I., B. E. Smith, I. M. Howat, T. Scambos, and T. Moon (2010), Greenland flow variability from ice-sheet-wide velocity mapping, *J. Glaciol.*, *56*(197), 415–430, doi:10.3189/002214310792447734.

Kleiven, H. F., E. Jansen, T. Fronval, and T. M. Smith (2002), Intensification of Northern Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma)–ice-rafted detritus evidence, Palaeogeography, Palaeoclimatology, *Palaeoecology*, *184*(3–4), 213–223, doi:10.1016/S0031-0182(01)00407-2.

Kleman, J. (1994), Preservation of landforms under ice sheets and ice caps, *Geomorphology*, *9*(1), 19–32, doi:10.1016/0169555X(94)90028-0.

Kleman, J., and C. Hättestrand (1999), Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum, *Nature*, *402*(6757), 63–66, doi:10.1038/47005.

Koppes, M. N., and D. R. Montgomery (2009), The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales, *Nat. Geosci.*, *2*(9), 644–647, doi:10.1038/ngeo616.

Mudd, S., M. Hurst, D. Milodowski, S. Grieve, F. Clubb, and D. Valters (2013), Land surface dynamics topography tool box.

Rose, K. C., F. Ferraccioli, S. S. R. Jamieson, R. E. Bell, H. Corr, T. T. Creyts, D. Braaten, T. A. Jordan, P. T. Fretwell, and D. Damaske (2013), Early East Antarctic Ice Sheet growth recorded in the landscape of the Gamburtsev Subglacial Mountains, *Earth Planet. Sci. Lett.*, *375*, 1–12, doi:10.1016/j.epsl.2013.03.053.

Rose, K. C., N. Ross, R. G. Bingham, H. F. J. Corr, F. Ferraccioli, T. A. Jordan, A. M. L. Brocq, D. M. Rippin, and M. J. Siegert (2014), A temperate former West Antarctic ice sheet suggested by an extensive zone of subglacial meltwater channels, *Geology*, *42*(11), 971–974, doi:10.1130/G35980.1.

Rose, K. C., N. Ross, T. A. Jordan, R. G. Bingham, H. F. J. Corr, F. Ferraccioli, A. M. Le Brocq, D. M. Rippin, and M. J. Siegert (2015), Ancient pre-glacial erosion surfaces preserved beneath the West Antarctic Ice Sheet, *Earth Surf. Dynam.*, *3*(1), 139–152, doi:10.5194/esurf-3-139-2015.

Ross, N., T. A. Jordan, R. G. Bingham, H. F. J. Corr, F. Ferraccioli, A. L. Brocq, D. M. Rippin, A. P. Wright, and M. J. Siegert (2014), The Ellsworth Subglacial Highlands: Inception and retreat of the West Antarctic Ice Sheet, *Geol. Soc. Am. Bull.*, *126*(1–2), 3–15, doi:10.1130/B30794.1.

Shreve, R. L. (1966), Statistical law of stream numbers, *J. Geol.*, *74*(1), 17–37.

Siegert, M. J., J. Taylor, and A. J. Payne (2005), Spectral roughness of subglacial topography and implications for former ice-sheet dynamics in East Antarctica, *Global Planet. Change*, *45*(1–3), 249–263, doi:10.1016/j.gloplacha.2004.09.008.

Sugden, D. E. (1974), Landscapes of glacial erosion in Greenland and their relationship to ice, topographic and bedrock conditions, in *Progress and Geomorphology*, *Institute of British Geographers Special Publication*, vol. 7, edited by E. H. Brown and R. S. Waters, pp. 177–195, Academic, London.

Sugden, D. E., and B. S. John (1976), *Glaciers and Landscape: A Geomorphological Approach*, Edward Arnold Ltd., London.

Summerfield, M. A. (1991), *Global Geomorphology: An Introduction to the Study of Landforms*, Longman Scientific and Technical, Harlow, Essex, England.

Wright, A. P., M. J. Siegert, A. M. Le Brocq, and D. B. Gore (2008), High sensitivity of subglacial hydrological pathways in Antarctica to small ice-sheet changes, *Geophys. Res. Lett.*, *35*, L17504, doi:10.1029/2008GL034937.

Young, D. A., et al. (2011), A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes, *Nature*, *474*(7349), 72–75, doi:10.1038/nature10114.