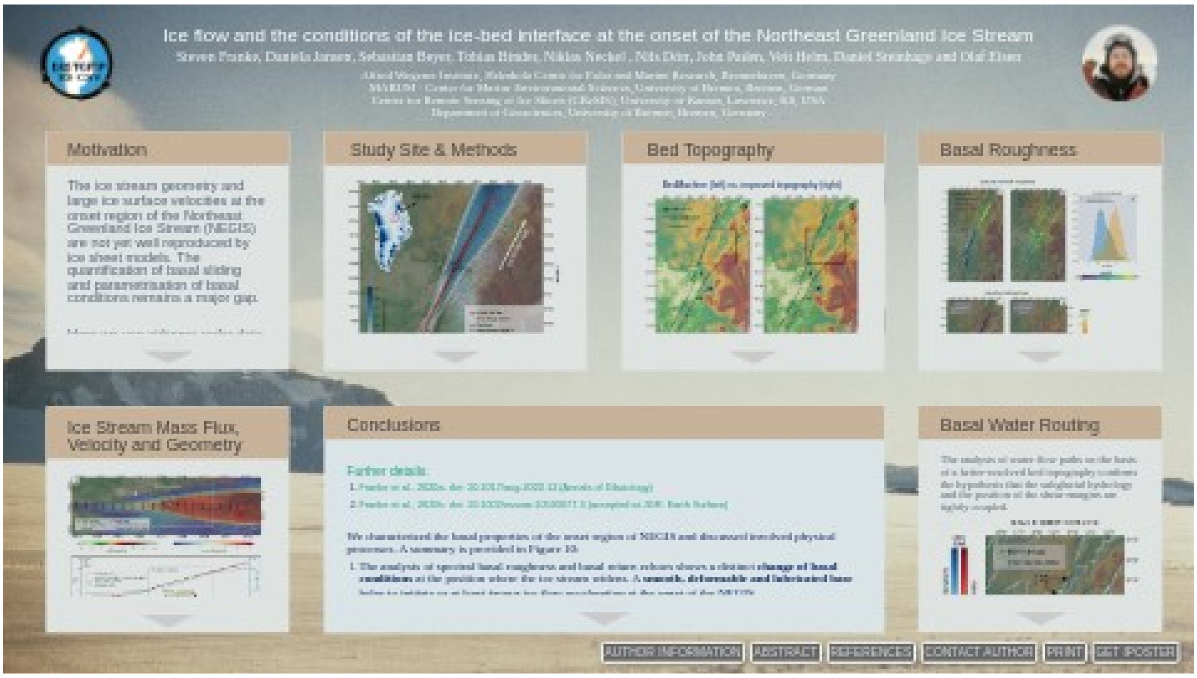
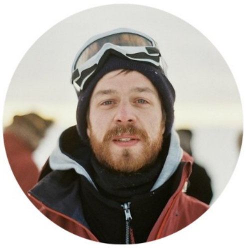
Ice flow and the conditions of the ice-bed interface at the onset of the Northeast Greenland Ice Stream



Steven Franke, Daniela Jansen, Sebastian Beyer, Tobias Binder, Niklas Neckel , Nils Dörr, John Paden, Veit Helm, Daniel Steinhage and Olaf Eisen

Alfred Wegener Institute, Helmholz Centre for Polar and Marine Research, Bremerhaven, Germany
MARUM - Center for Marine Environmental Sciences, University of Bremen, Bremen, German
Center for Remote Sensing of Ice Sheets (CReSIS), University of Kansas, Lawrence, KS, USA
Department of Geosciences, University of Bremen, Bremen, Germany



PRESENTED AT:

AGU FALL MEETING
Online Everywhere | 1–17 December 2020

MOTIVATION

The ice stream geometry and large ice surface velocities at the onset region of the Northeast Greenland Ice Stream (NEGIS) are not yet well reproduced by ice sheet models. The quantification of basal sliding and parametrisation of basal conditions remains a major gap.

Here we use airborne radar data from AWI's ultra-wideband radar system to analyze the basal conditions of the onset of the (NEGIS). We perform a spectral roughness analysis to characterize the pattern of the bed return signals and investigate the subglacial roughness parallel and perpendicular to ice flow. Based on an improved bed elevation model, we investigate subglacial water pathways. We then combine these data with an analysis of ice mass flux at the ice stream.

STUDY SITE & METHODS

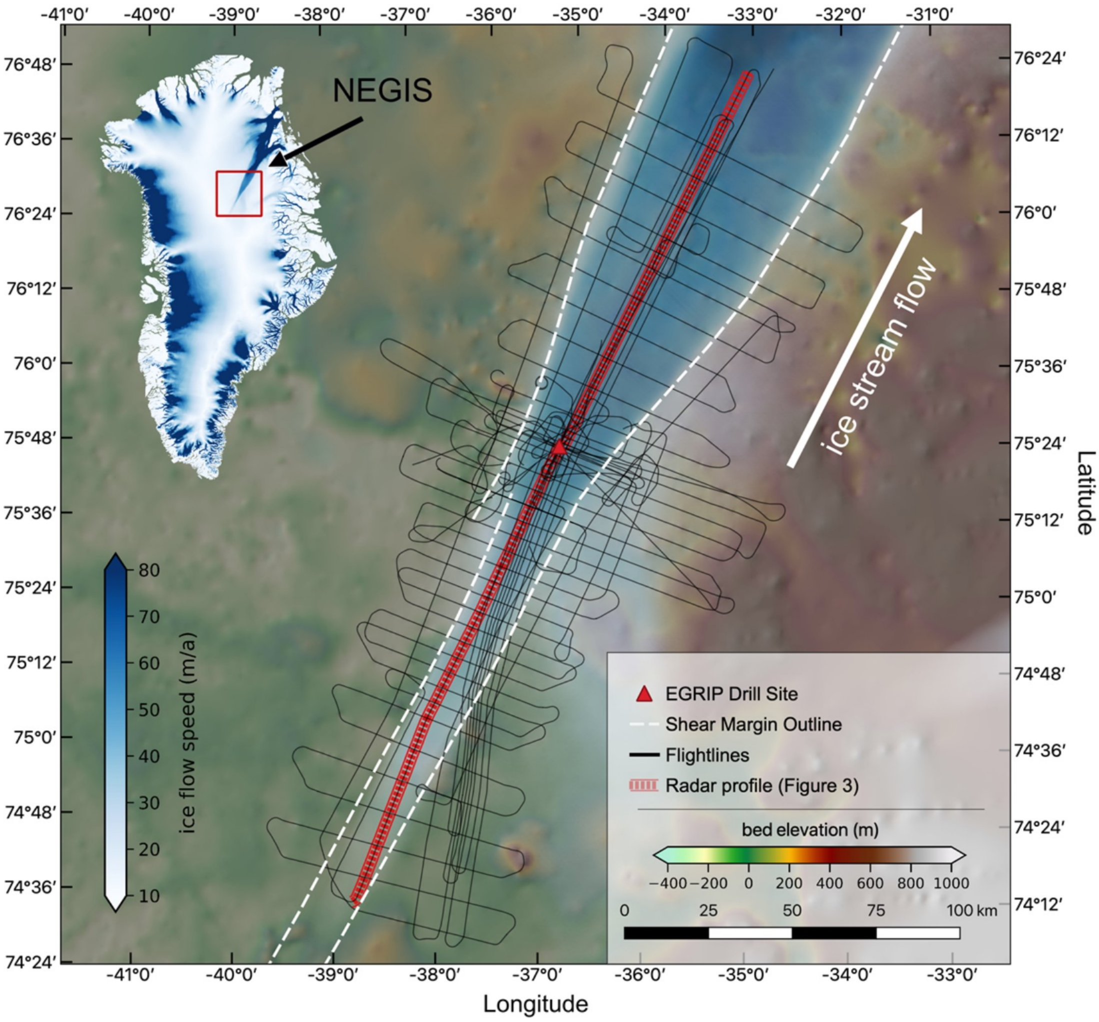


Figure 1: Overview of the survey area in the interior of the Greenland Ice Sheet at the onset of fast flow of the NEGIS. The black lines, which are centred at the EGRIP drill site, represent the survey profiles of the EGRIP-NOR-2018 airborne UWB radar survey (Franke et al., 2020). The white dashed lines show the outline of the shear margins (determined from satellite imagery) and the dashed red line the radar profile shown in Figure 4. Bed elevation is referenced to mean sea level(EIGEN-6C4 geoid (F¨orste et al., 2007), this reference applies to all other maps showing the bed elevation) and ice flow velocity is based on the data set of Joughin et al. (2017) and is shown in blue colour code for velocities larger than 10 m/a. The projection of this map and all following maps are shown in the coordinate system EPSG 3413 (WGS84 / NSIDC Sea Ice Polar Stereographic North).

In the study area, the NEGIS accelerates from ~10 to 80 m/aover a distance of roughly 300 km and widens from ~20 km in the upstream boundary of our survey area to ~65 km further downstream (Figure 1). The profile spacing of across-flow profiles is 5 km in the central part of the survey area, near the drill site of the East Greenland Ice-core Project (EGRIP; http://eastgrip.org (http://eastgrip.org)), and10 km further upstream and downstream. For the rest of this poster, we will refer to upstream and downstream as the regions upstream and downstream of the EGRIPdrill site, respectively.

In our study we use the following methods to analyze the conditions of the bed with radar data (Figure 1M):

1. We define basal roughness as the relative vertical and horizontal variation of the topography of the ice-bed interface. In our analysis, we calculate two parameters (ξ and η), with a spectral analysis approach (Li et al., 2010; Cooper et al., 2019).

2. To characterize the basal scattering, we follow the approach of Oswald and Gogineni (2008) which has been adapted and extensively used in Greenland by Cooper et al.

(2019); Jordan et al. (2016, 2017) and Jordan et al. (2018). The so called 'waveform abruptness' gives us information about the small-scale roughness.

3. We compute (potential) subglacial water pathways from the gradient in hydrological potential

4. In order to calculate the ice mass flux in the survey area, we employed 20 flux gates orientated perpendicular to the ice flow direction.

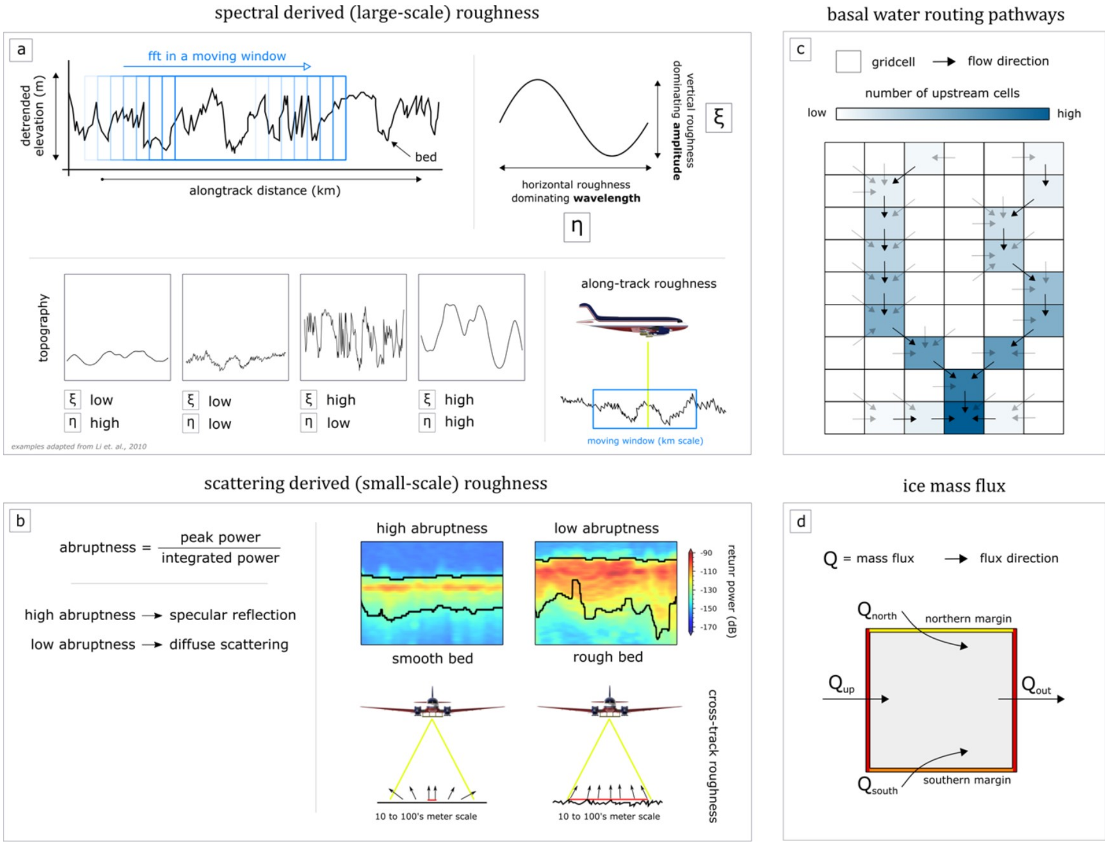


Figure 1M: Summary of methods to characterize the basal conditions: (a) spectral roughness, (b) waveform abruptness, (c) basal water routing pathways and (d) ice mass flux calculations.

BED TOPOGRAPHY

BedMachine (left) vs. improved topography (right)

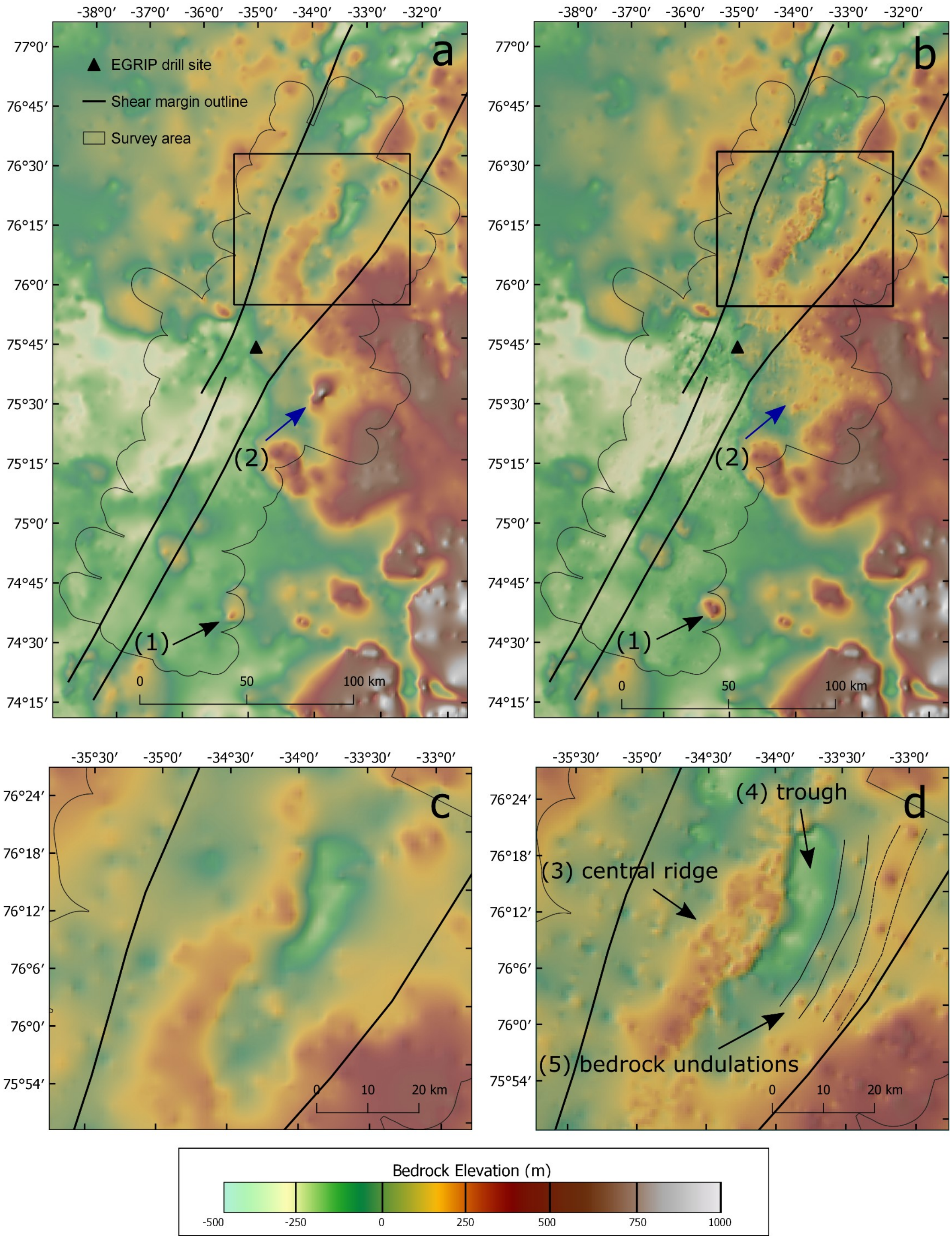


Figure 2: Bed topography of (a) BedMachine v3 (Morlighem and others, 2017 and (b) the EGRIP-NOR-2018 bed topography derived from our ice thickness data. A magnified view for the area upstream of the EGRIP drill site for both models (a and b) is shown on the two lower images (c and d, respectively). Two locations with strong elevation differences are marked with a black and blue arrow (feature 1 and 2).

Our data yield a new detailed model of ice-thickness distribution and basal topography in the region. The enhanced resolution of our bed topography model shows features which we interpret to be caused by erosional activity, potentially over several glacial-interglacial cycles.

Furthermore, we detect internal reflections which have been interpreted as bedrock before (feature 2 in Figure 2a,b and Figure 3).

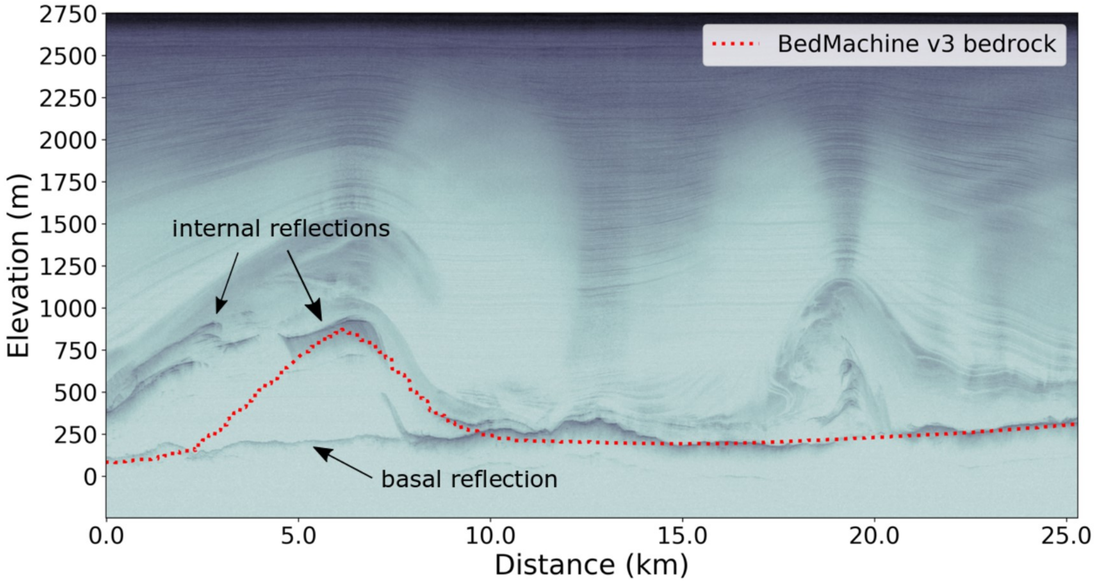


Figure 3: Echogram from profile 20180508_06_003 along the point of our largest deviation in ice thickness (blue mark in Fig. 2). The dashed red line represents the bed elevation as used in BedMachine v3 (Morlighem and others, 2017). The high peak at 6 km distance along the profile and ~750 m elevation correlates with a high energy internal reflection located in

an area of folded internal layers. Underneath that undulation, a fainter laterally straight and coherent reflection with a lower amplitude is visible, which we interpret as the basal reflection.

BASAL ROUGHNESS

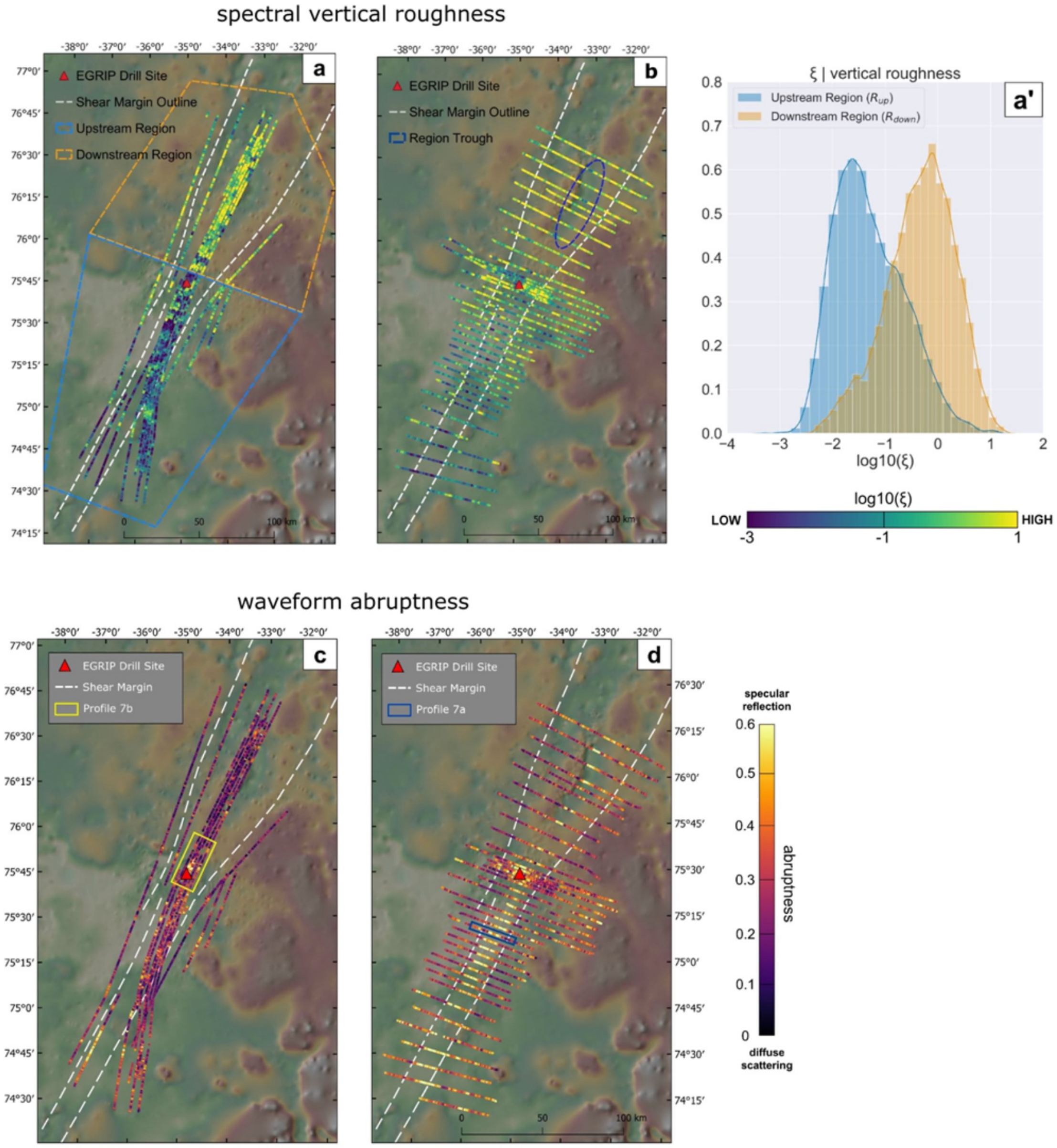


Figure 4: Survey area at the NEGIS showing (a) along- and (b) across-flow profiles of the vertical roughness parameter ξ.The background map represents the EGRIP-NOR-2018 bed topography of Franke et al. (2020) in meters, referenced to mean sea-level (EIGEN-6C4 geoid). Histogram a' shows the distribution of ξ for the along-flow profiles for the upstream and downstream region (orange and blue outline ina and b). Panel (c) and (d) show waveform abruptness for profiles oriented along-flow and across-flow. Waveform abruptness is expressed as the ratio between the maximum BRP and the integrated bed return power and is thus unitless.

Our results reveal a regional change in basal roughness from the upstream towards the downstream part in our study area on the NEGIS (Figure 4a, a' and b). Furthermore, we detect a directional dependent difference in waveform abruptness (Figure 4c and d).

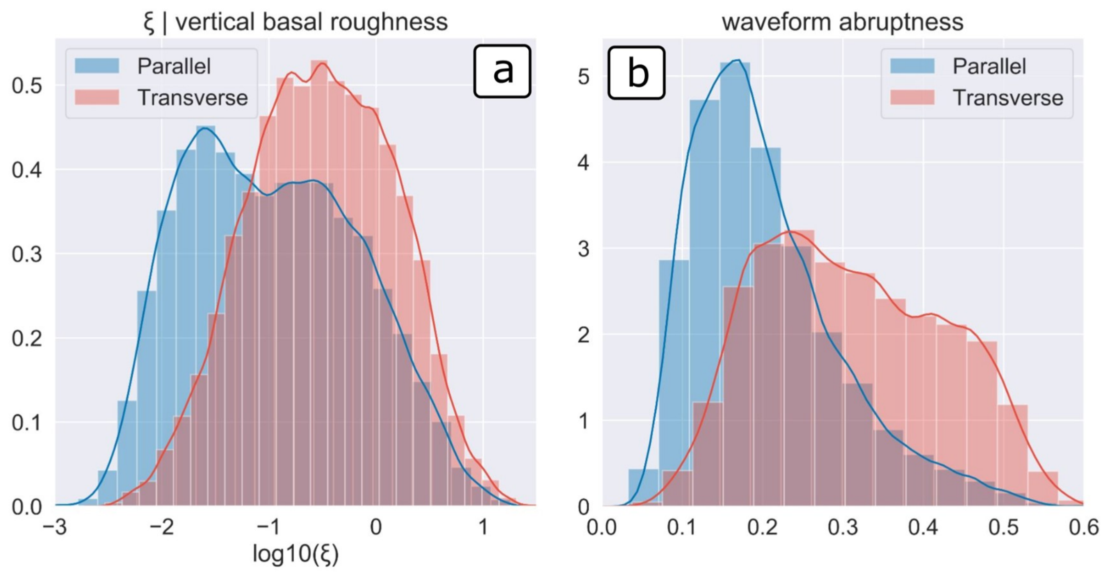


Figure 5: Histograms presenting the distribution of (a) vertical basal roughness and (b) waveform abruptness for profiles oriented along- and across-flow for the location inside of the ice stream. Blue bins represent along- and red bins across-flow profiles. The y-axis shows the kernel density estimation.

Furthermore, we detect a bed roughness anisotropy concerning the ice flow direction, indicating streamlining parallel to ice flow (Figure 5).

Off-nadir reflections from the ice–bed interface in the centre of the ice stream confirm a streamlined bed with elongated subglacial landforms (Figure 6 and 7).

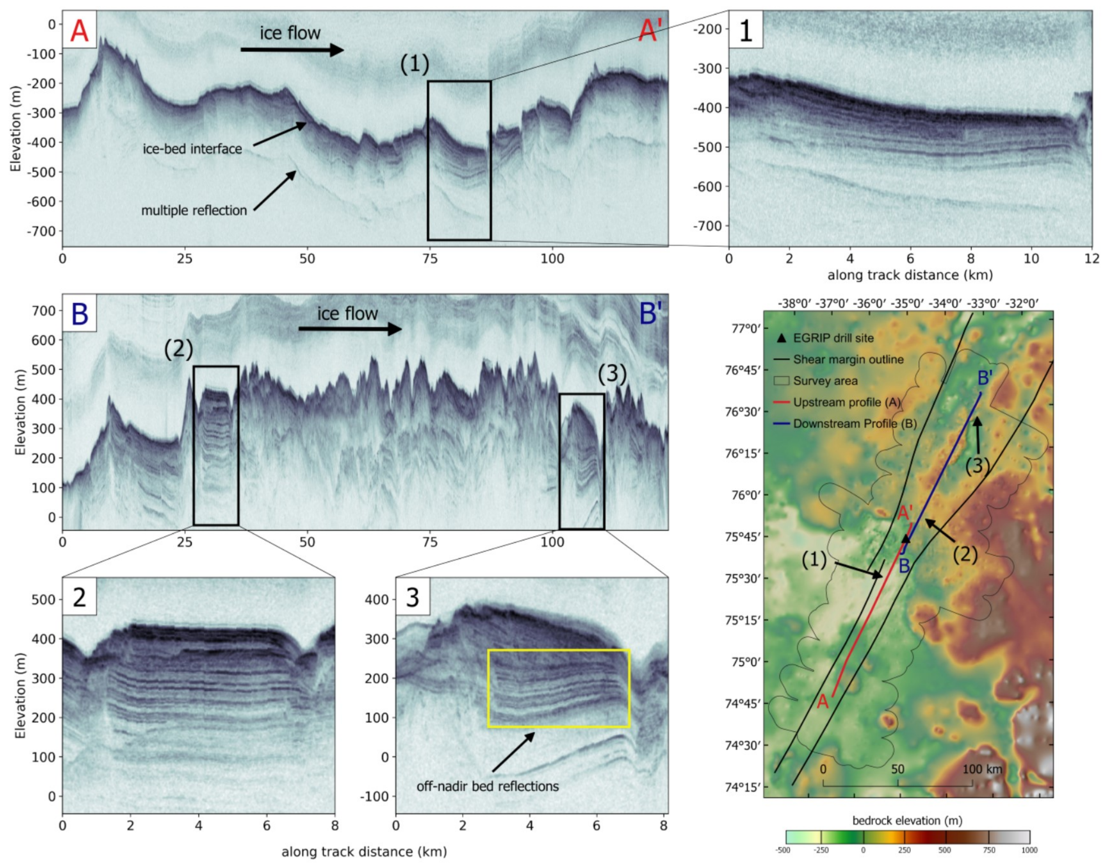


Figure 6: A set of radargrams from the upstream (A) and downstream part (B) of the survey area oriented parallel to ice flow. The data were recorded

with an increased radar cross-track beam angle. Subsections of the radargrams indicating the location of off-nadir reflections are shown in the radargrams 1, 2 and 3. An example of the off-nadir bed reflection pattern in the radargram is indicated in radargram 3 with the yellow outline. The position and the orientation of the radargrams (A to A′ in red and B to B′ in blue) as well as the location of the off-nadir reflection patterns 1, 2 and 3 are indicated in the map in the lower right corner.

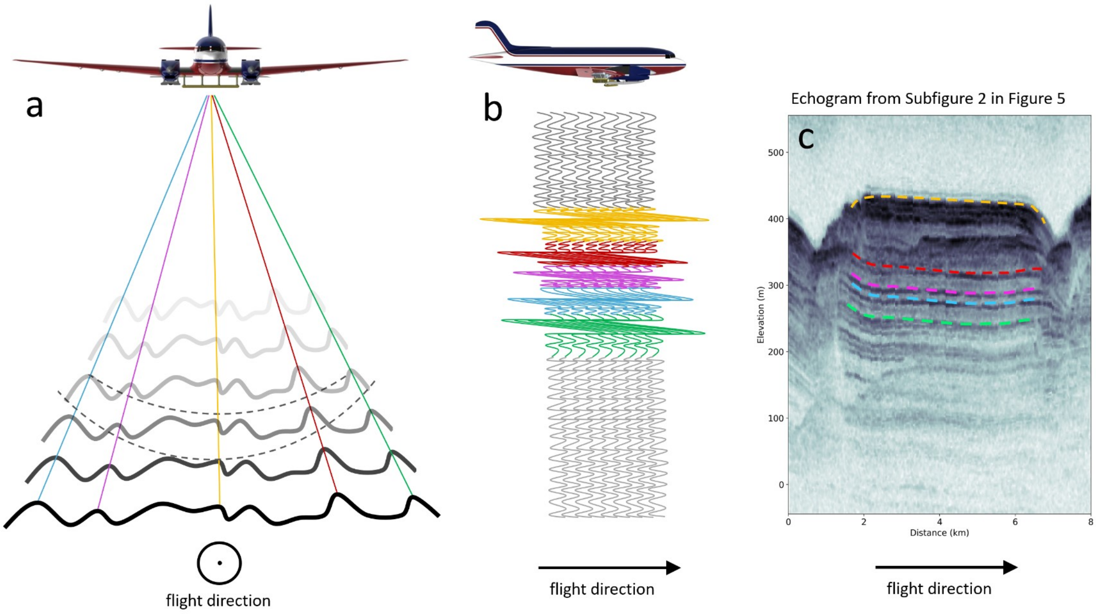


Figure 7: This sketch shows how the bed structures of our interpretation of basal off-nadir reflections can look like. (a) Side reflections are scattered toward the receiver from elongated landforms aligned parallel to the flight trajectory. The black lines represent the bed reflector at different positions along the flight path. The different off-nadir reflections, which are most likely caused by scattered reflections by the elongated structures, are shown here in five different colors.(b) If the structure is parallel to the flight direction, a similar reflection pattern is recorded in the traces along the flight trajectory. (c) In the example of echogram section of the profile 20180515_01_007, the recorded signal could potentially look as indicated by the colored dashed layers. Plane model by courtesy of University of Kansas, Department of Engineering (2015).

ICE STREAM MASS FLUX, VELOCITY AND GEOMETRY

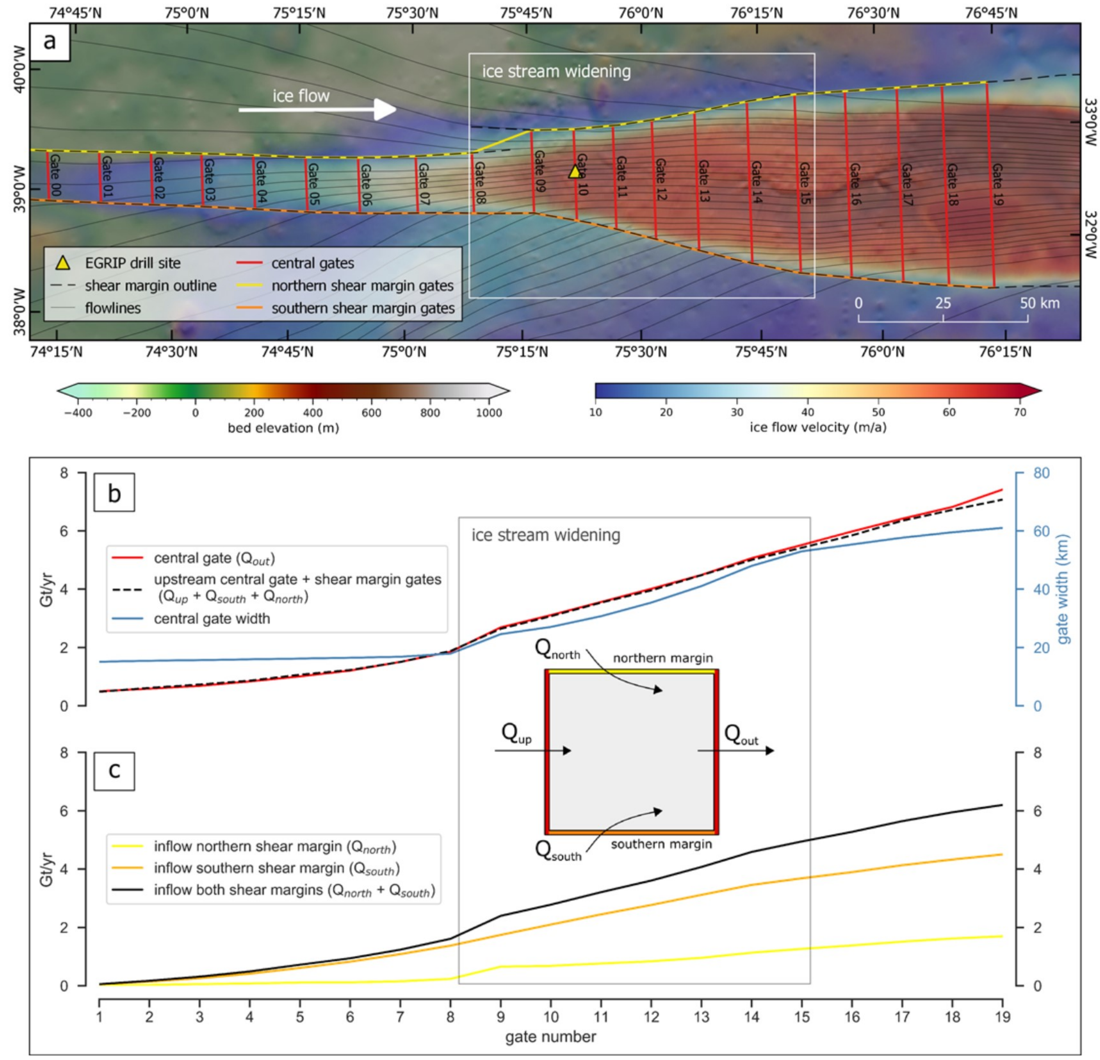


Figure 9: Fluxgate analysis of the onset of the NEGIS. Panel (a) shows the position of central fluxgates (red) and flux gates at the shear margins (yellow and orange, respectively). The location where the ice stream widens is marked with a white outline. Panel (b) shows the mass flux (in Gt/yr)through the central gates (Qout; red line) in comparison to the sum of the respective upstream central gate (Qup) and the corresponding shear margin gates (Qsouth+Qnorth; black dashed line). The blue line represents the width of the central gates. The cumulative mass flux through the northern and southern shear margin (as well as the sum of both) is shown in panel (c).

The analysis of flux gates shows that the additional incoming ice mass through the shear margins is evacuated by two different mechanisms. In the upstream regime, we observe that flowlines converge (Figure 9a), which is compensated by along-flow stretching due to ice stream acceleration. Downstream of fluxgate 8, ice flow acceleration decreases, the ice stream widens and flowlines do neither converge nor diverge. Hence, the widening of the ice stream has two interdependent effects:

1. (i) Excess ice mass can be evacuated without ice stream acceleration.
2. (ii) More ice is added to the system on a shorter distance due to the widening.

Disregarding the initial cause for ice stream widening we observe a strong interdependence between the roughness of the bed, ice surface flow velocity and the geometry of the ice stream.

CONCLUSIONS

Further details:

1. Franke et al., 2020a. doi: 10.1017/aog.2020.12 (Annals of Glaciology) (https://doi.org/10.1017/aog.2020.12)
2. Franke et al., 2020b. doi: 10.1002/essoar.10503077.3 (accepted at JGR: Earth Surface) (https://doi.org/10.1002/essoar.10503077.3)

We characterized the basal properties of the onset region of NEGIS and discussed involved physical processes. A summary is provided in Figure 10:

1. The analysis of spectral basal roughness and basal return echoes shows a distinct **change of basal conditions** at the position where the ice stream widens. A **smooth, deformable and lubricated base** helps to initiate or at least favour ice flow acceleration at the onset of the NEGIS.
2. The **positioning of the shear margins** and the pathways of subglacial water flow shows an immediate relationship between the ice stream extent and the subglacial hydrology system.
3. Ice surface velocity, shear margin positioning and the pattern and intensity of the bed reflection are influenced by different scales of basal roughness.

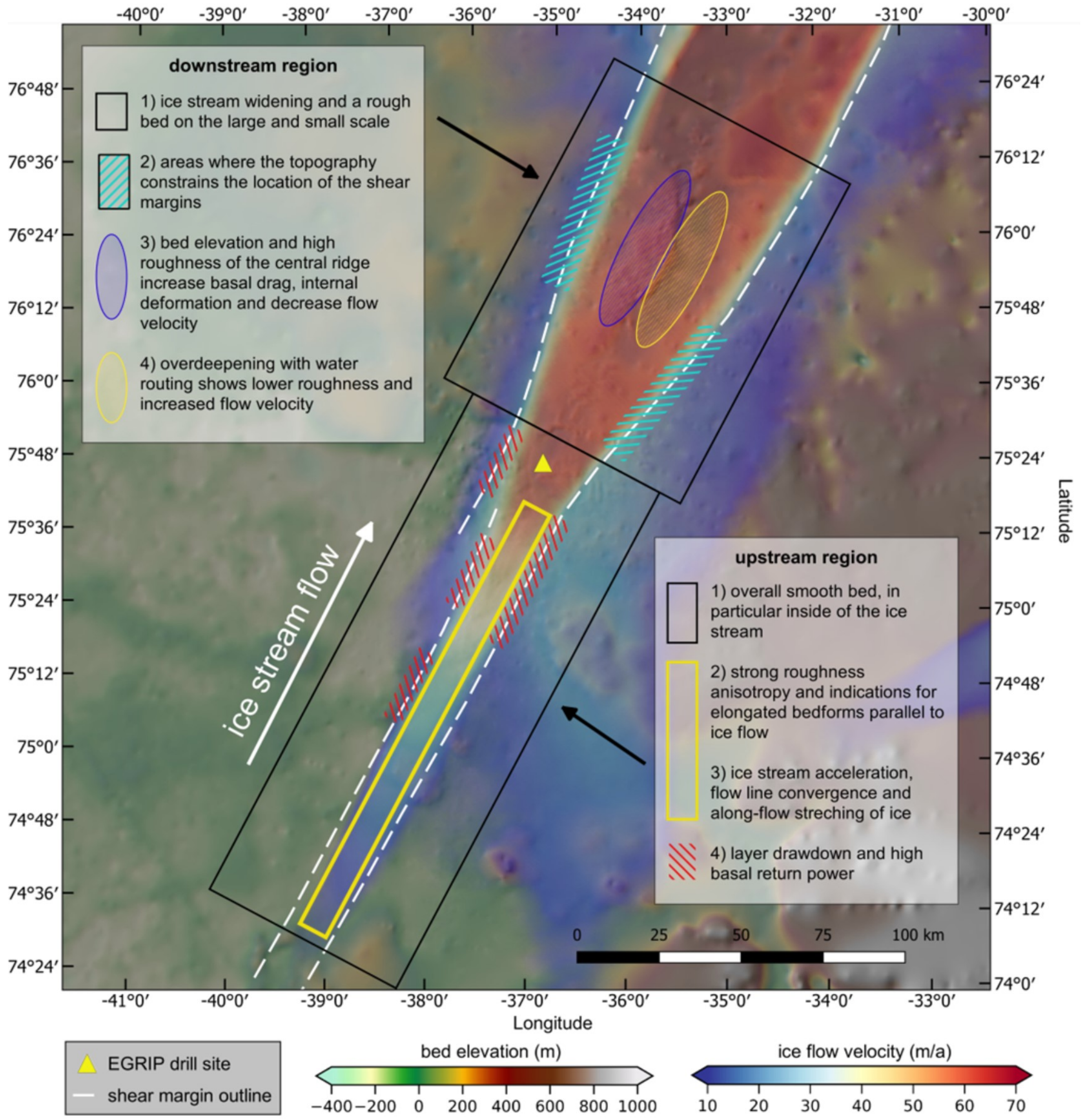


Figure 10: Summary of the basal properties of the (a) upstream and the (b) downstream survey region.

Regionally extending our interpretation, the involved processes could have a significant impact on the ice dynamics and ice stream catchments of Greenland in a warming climate. Changes in the surface mass balance in the upstream catchment, which is currently relatively small, could reorganize the location of the shear margins. It is possible that this could either initiate faster ice flow even further upstream, and/or take up a larger catchment area and, thus, increase the amount of ice discharge of the GrIS.

BASAL WATER ROUTING

The analysis of water flow paths on the basis of a better-resolved bed topography confirms the hypothesis that the subglacial hydrology and the position of the shear margins are tightly coupled.

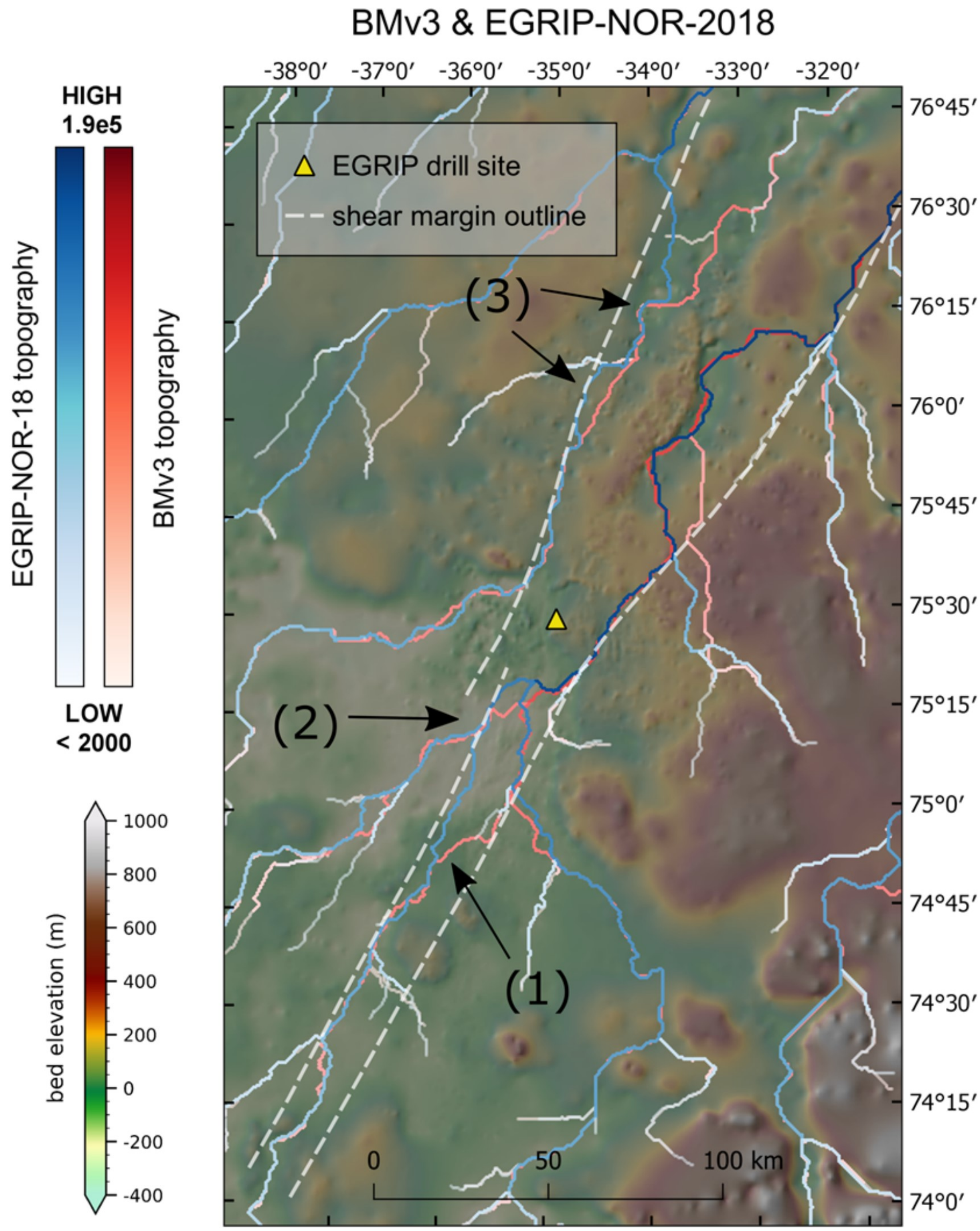


Figure 8: Basal water routing pathways calculated based on EGRIP-NOR-2018 bed elevation(Franke et al. (2020); in blue) as well as pathways calculated with the bed elevation model BMv3(Morlighem et al. (2017); in red). The basal water routing colour saturation represents the number of accumulated upstream cells. Pixels containing less than 2000 upstream cells are transparent. High values and dark colours represent pathways that transport larger amounts of upstream cells. Features(1) – (3) present locations where the routing pathways from the two bed elevation models show the largest deviations. The background map represents the bed elevation of the EGRIP-NOR-18 data.

In the upstream part, hydraulic pathways indicate that water is routed into the ice stream from neighbouring areas. Further downstream, where the ice stream widens, basal water is pushed towards and beyond the shear margin, partly because of the local topography and lithological properties but also partly because of surface slopes of the ice surface. This leads to less resistant basal properties at the margins and enables a widening of the ice stream.

AUTHOR INFORMATION

Steven Franke[1], Daniela Jansen[1], Sebastian Beyer[2], Tobias Binder[1], Niklas Neckel[1], Nils Dörr[1], John Paden[3], Veit Helm[1], Daniel Steinhage[1] and Olaf Eisen[1,4]

[1] Alfred Wegener Institute, Helmholz Centre for Polar and Marine Research, Bremerhaven, Germany
[2] MARUM - Center for Marine Environmental Sciences, University of Bremen, Bremen, German
[3] Center for Remote Sensing of Ice Sheets (CReSIS), University of Kansas, Lawrence, KS, USA
[4] Department of Geosciences, University of Bremen, Bremen, Germany

ABSTRACT

The Northeast Greenland Ice Stream (NEGIS) is an important dynamic component contributing to the total mass balance of the Greenland ice sheet, as it reaches up to the central divide and drains 12% of the ice sheet. The ice stream geometry and surface velocities in the onset region of the NEGIS are not yet sufficiently well reproduced by ice sheet models. We present an assessment of the basal conditions of the onset region in a systematic analysis of airborne ultra-wideband radar data. Our data yield a new detailed model of ice-thickness distribution and basal topography in the upstream part of the ice stream. We observe a change from a smooth to a rougher bed where the ice stream widens from 10 to 60 km, and a distinct roughness anisotropy, indicating a preferred orientation of subglacial structures. The observation of off-nadir reflections that are symmetrical to the bed reflection in the radargrams suggests that these structures are elongated subglacial landforms, which in turn indicate potential streamlining of the bed. Together with basal water routing pathways, our observations hint to two different zones in this part of the NEGIS: an accelerating and smooth upstream region, which is collecting water, with reduced basal traction, and in the further downstream part, where the ice stream is slowing down and is widening, with a distribution of basal water towards the shear margins. Our findings support the hypothesis that the NEGIS is strongly interconnected to the subglacial water system in its onset region, but also to the subglacial substrate and morphology.

REFERENCES

Christianson K and 7 others (2014) Dilatant till facilitates ice-stream flow in northeast Greenland. Earth and Planetary Science Letters 401, 57–69. doi: 10.1016/j.epsl.2014.05.060

Cooper M A and 6 others (2019). Subglacial roughness of the Greenland Ice Sheet: relationship with contemporary ice velocity and geology. The Cryosphere, 13(11):3093–3115, nov 2019. doi:10.5194/tc-13-3093-2019

Franke S and 7 others (2020). Bed topography and subglacial landforms in the onset region of the Northeast Greenland Ice Stream. Annals of Glaciology 61 (81), 143–153. https://doi.org/10.1017/aog.2020.12

Förste C and 11 others (2007)The GeoForschungsZentrum Potsdam/Groupe de Recherchede Geod´esie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1 and EIGEN-GL04C.Journal of Geodesy, 82(6):331–346, oct 2007. doi: 10.1007/s00190-007-0183-8

Jordan T M and 7 others (2016) An ice-sheet-wide framework for englacial attenuation from ice-penetrating radar data. The Cryosphere, 10(4):1547–1570, jul 2016. doi: 10.5194/tc-10-1547-2016.

Jordan T M and 6 others (2017) Self-affine subglacial roughness: consequences for radar scattering and basal water discrimination in northern Greenland. The Cryosphere, 11(3):1247–1264, may 2017. doi: 10.5194/tc-11-1247-2017

Joughin I, Smith BE and Howat IM (2018) A complete map of Greenland ice velocity derived from satellite data collected over 20 years. Journal of Glaciology 64(243), 1–11. doi: 10.1017/jog.2017.73

Li and 6 others (2010) Characterization of subglacial landscapes by a two-parameter roughnessindex.Journal of Glaciology, 56(199):831–836, 2010. doi: 10.3189/002214310794457326

Morlighem M and 31 others (2017) BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. Geophysical Research Letters 44(21), 11051–11061.
doi: 10.1002/2017GL074954

Oswald G K A and Gogineni S.P. (2008) Recovery of subglacial water extent from Greenland radar survey data.Journal of Glaciology, 54(184):94–106, 2008. doi: 10.3189/002214308784409107