GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G46772.1

Manuscript received 16 July 2019
Revised manuscript received 7 October 2019
Manuscript accepted 18 November 2019

Published online 3 January 2020

Linking postglacial landscapes to glacier dynamics using swath radar at Thwaites Glacier, Antarctica

N. Holschuh[1,2]*, K. Christianson[2], J. Paden[3], R.B. Alley[4] and S. Anandakrishnan[4]
[1]Department of Geology, Amherst College, Amherst, Massachusetts 01002-5000, USA
[2]Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195-1310, USA
[3]Center for Remote Sensing of Ice Sheets, University of Kansas, Lawrence, Kansas 66045, USA
[4]Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, USA

ABSTRACT

Ice sheets reshape Earth's surface. Maps of the landscape formed by past ice sheets are our best tool for reconstructing historic ice sheet behavior. But models of glacier erosion and deposition that explain mapped features are relatively untested, and without observations of landforms developing *in situ*, postglacial landscapes can provide only qualitative insight into past ice sheet conditions. Here we present the first swath radar data collected in Antarctica, demonstrating the ability of swath radar technology to map the subglacial environment of Thwaites Glacier (West Antarctica) at comparable resolutions to digital elevation models of deglaciated terrain. Incompatibility between measured bedform orientation and predicted subglacial water pathways indicates that ice, not water, is the primary actor in initiating bedform development at Thwaites Glacier. These data show no clear relationship between morphology and glacier speed, a weak relationship between morphology and basal shear stress, and highlight a likely role for preexisting geology in glacial bedform shape.

INTRODUCTION

Post-glacial landscapes contain an integrated record of subglacial processes during glaciation, periglacial processes during retreat, and subsequent alteration during interglacial periods. Some observed landforms represent the "last gasp" of the glaciers—melt-out features including kettles, kames, and eskers record the shutdown of the glacio-fluvial system, the end of sediment transport, and the relict ice left behind as ice flow ceased (Benn and Evans, 2010). Other landforms, such as rogen (ribbed) moraines, drumlins, and mega-scale glacial lineations (MSGLs), are generally thought to form during active ice flow, a product of the coupled ice-water-rock system at the base of glaciers (Fowler, 2018). As models of landform generation proliferate, new methods for observing the subglacial environment are also being developed, which allow for some of the first tests of model performance against *in situ* data.

Arguably the most active debate over glacial bedforms centers on streamlined hills: drumlins and MSGLs. Some observations might indicate that these features form by an inherent instability in the coupled till-ice-water system at glacier beds: they are pervasive across the high latitudes (Hättestrand and Clark, 2006); bedform fields are often organized, with preferential spacing in both the flow-parallel and flow-perpendicular directions (Clark et al., 2018); and bedform population statistics show overlap in the morphologies of ribbed moraines, drumlins, and MSGLs, indicating they may exist along a morphological continuum (Spagnolo et al., 2014; Ely et al., 2016). But MSGLs and drumlins exhibit a large range of internal structures (Stokes et al., 2011) and are also found in atypical or non-steady glacial settings (Benediktsson et al., 2016; Ives and Iverson, 2019). Whether drumlins and MSGLs form as the result of a common process or simply share a common form remains an outstanding question.

Through radar technology development (Paden et al., 2010; Jezek et al., 2011), it is now possible to collect images of modern glacier beds at fine resolution over large areas with a single pass (tens of meters resolution, >2 km swath width), imaging nearer the quality of lidar and multibeam swath bathymetry commonly used to identify glacial landforms in deglaciated landscapes (e.g., Ó Cofaigh et al., 2002; Atkinson et al., 2014). In this study, we apply swath processing techniques to radar data collected during the 2009–2010 austral summer, producing images of bedforms at the base of Thwaites Glacier. Our goal is to use these data to test models of bedform generation, comparing known glaciological conditions with observed bedform morphology.

Some models rely on preexisting heterogeneity in the rock and till underlying glaciers to explain the size and shape of observed bedforms (e.g., Boulton, 1987); these are more difficult to test with morphological data alone. But, like models of dunes and ripples on the sea floor, instability models of drumlin and MSGL formation are framed as fluid dynamics problems; thus, in instability models, bedform morphology depends primarily on the properties of the over-flowing fluid (be it ice or water), and we can use both directly measured and inferred glacier properties to test model predictions of bedform shape.

SWATH RADAR IMAGING AT THWAITES GLACIER

Substantial effort has been devoted to measuring bedforms under modern glaciers, mapping subglacial topography at high resolution using conventional, nadir-focused radar and seismic techniques (e.g., King et al., 2009; Smith and Murray, 2009; Bingham et al., 2017). These data sets provided the best existing observations of glacier bedforms in their modern glaciological context. However, such data have inherent cross-track resolution limitations, and trade off cross-track resolution with regional coverage. For swath radar data, cross-track resolution is independent of the regional survey design, allowing for imaging of glacier bedforms at fine resolution across a range of glacial settings with lower logistical cost.

The data presented here were collected over Thwaites Glacier (Figs. 1A and 1B), one of the fastest-flowing and most rapidly changing glaciers in Antarctica. These data were collected by Twin Otter aircraft using the 6-element array of

*E-mail: nholschuh@amherst.edu

CITATION: Holschuh, N., et al., 2020, Linking postglacial landscapes to glacier dynamics using swath radar at Thwaites Glacier, Antarctica: Geology, v. 48, p. 268–272, https://doi.org/10.1130/G46772.1

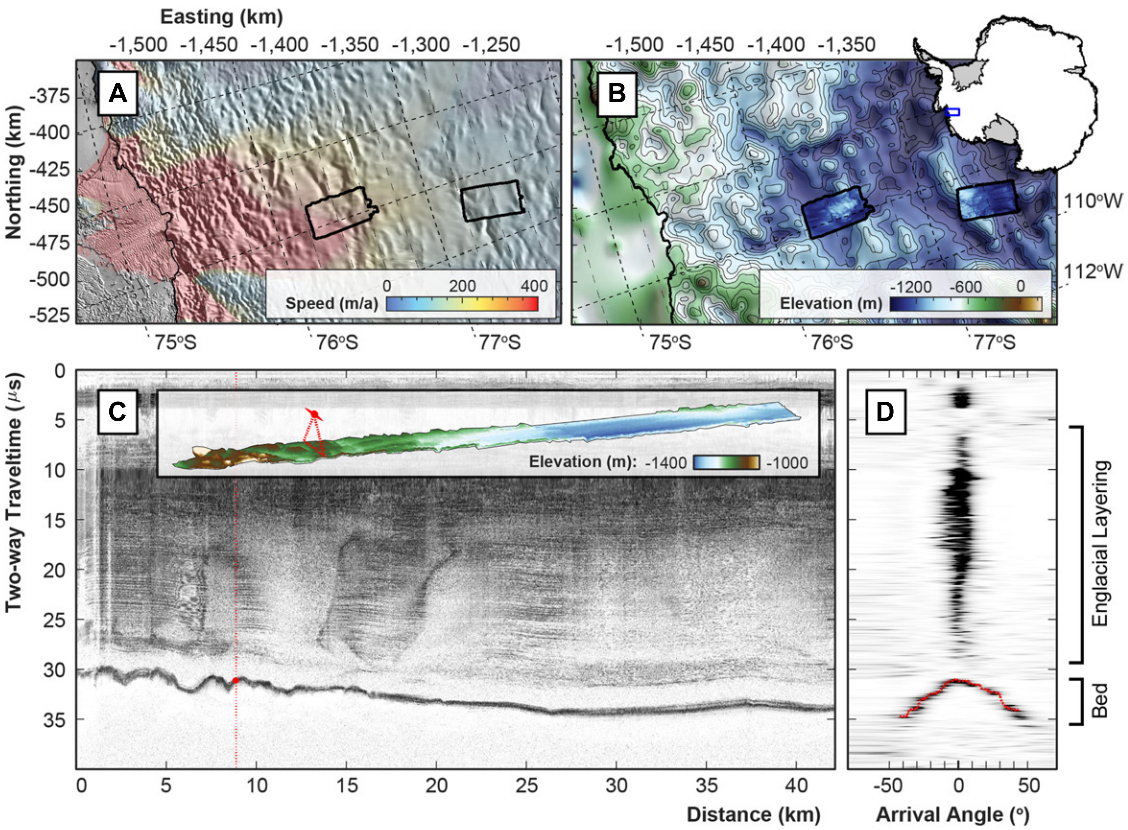

Figure 1. The regional setting in Antarctica (A,B) for high-resolution topography derived from swath radar data (C,D). For each trace of a nadir-focused radar image (C) we produced an accompanying cross-track image (D, from the red trace in C), in which the bed is digitized to produce a final topography swath (C inset).

the Multichannel Coherent Radar Depth Sounder (MCoRDS/I) radar system (Rodríguez-Morales et al., 2013). Assuming targets are stationary in time, phase differences in the arrival of backscattered energy from sequential acquisitions are used to position subsurface targets in the along-track dimension (i.e., synthetic aperture focusing). This results in an image of the subsurface that implicitly assumes all reflections originate at nadir (Fig. 1C). Because the MCoRDS/I system has a cross-track antenna array, information from sequential acquisitions can be combined with phase differences in arrivals between receiver elements, thereby determining the direction of arrival for energy in both the along-track and across-track directions, mapping the subsurface in three dimensions (Paden et al., 2010). Digitizing the bed reflector in cross-track images (Fig. 1D; following Al-Ibadi et al., 2017) produces topography swaths ~2 km wide for this data set.

BEDFORM CHARACTERIZATION

Three classes of bedforms are pervasive in the subglacial environment of Thwaites Glacier (Figs. 2B and 2D):

(1) stoss-side and lateral moats,
(2) strongly tapered, elongate crag-and-tails, and
(3) weakly tapered or longitudinally symmetric till bedforms (lineations).

These were expected for warm-based, fast-flowing glaciers like Thwaites, but have never been imaged at the level of detail presented here. Without the need to interpolate, subglacial features are imaged at resolutions (~25 m along track and across track) required for morphometric analysis (Napieralski and Nalepa, 2010).

Stoss-side moats are common under Thwaites Glacier. They exist at a variety of scales, ranging from 500 m to 2000 m wide, and 50 m to 100 m deep (Fig. 2, yellow rectangles). Once exposed at Earth's surface in postglacial landscapes, these moats can act as sediment traps, with secondary in-fill that masks their formation depth (as in the moat occupied by the modern fluvial system seen in Figure 2E, i). Their depth at Thwaites Glacier appears to increase with the size of the ice-flow obstruction around which they form. While this work focuses on testing instability models for elongate bedforms, future work will focus on quantifying moat formation using these observations.

Informed by seismic surveys co-located with our upstream grid (Muto et al., 2019), we separate the observed linear features into two broad categories: (1) crag-and-tails (sediment-mantled, resistant features, up to 5 km wide and 200 m to 300 m tall, defined by an upstream protruding "crag" and strong down-flow taper; Fig. 2, orange rectangles); and (2) MSGLs (elongate till bedforms with scales ranging from 100 m to 2000 m wide and 10 m to100 m high; Fig. 2, red). MSGLs were picked for morphometric analysis based on a two-dimensional Fourier filter, excluding features with obvious crags, dominant transverse wavelengths >1 km, or length-to-width ratios of <10. Where subglacial relief is low, MSGLs are seen parallel to the surface ice flow vector, overriding longer-wavelength features including the crag-and-tails. Where flow obstructions are large, MSGLs curve slightly around obstructions to flow, a phenomenon also seen in postglacial landscapes (Fig. 2E, i).

COMPARING OBSERVATIONS AND INSTABILITY MODELS

If one assumes till transport rates scale with ice pressure at the base of a glacier, ice flow alone could explain how initial perturbations in till thickness become continuous, flow-transverse ridges (Hindmarsh, 1998; Schoof, 2007). But instability models that can produce the systematic, transverse regularity in bed features that characterize drumlins and MSGLs require additional processes. Existing instability models invoke either viscous lateral flow of till driven by local pressure gradients (Barchyn et al., 2016), lateral variations in till transport by spiral flows in basal ice (Schoof and Clarke, 2008), or lateral variations in till transport by rilling of subglacial water (Fowler, 2010) (see the GSA Data Repository[1] for in-depth model description and quantification).

[1]GSA Data Repository item 2020074, supplementary material describing hydraulic potential calculations and instability models, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org. Radar data and gridded topographies are accessible through the University of Washington ResearchWorks Archive (http://hdl.handle.net/1773/44950).

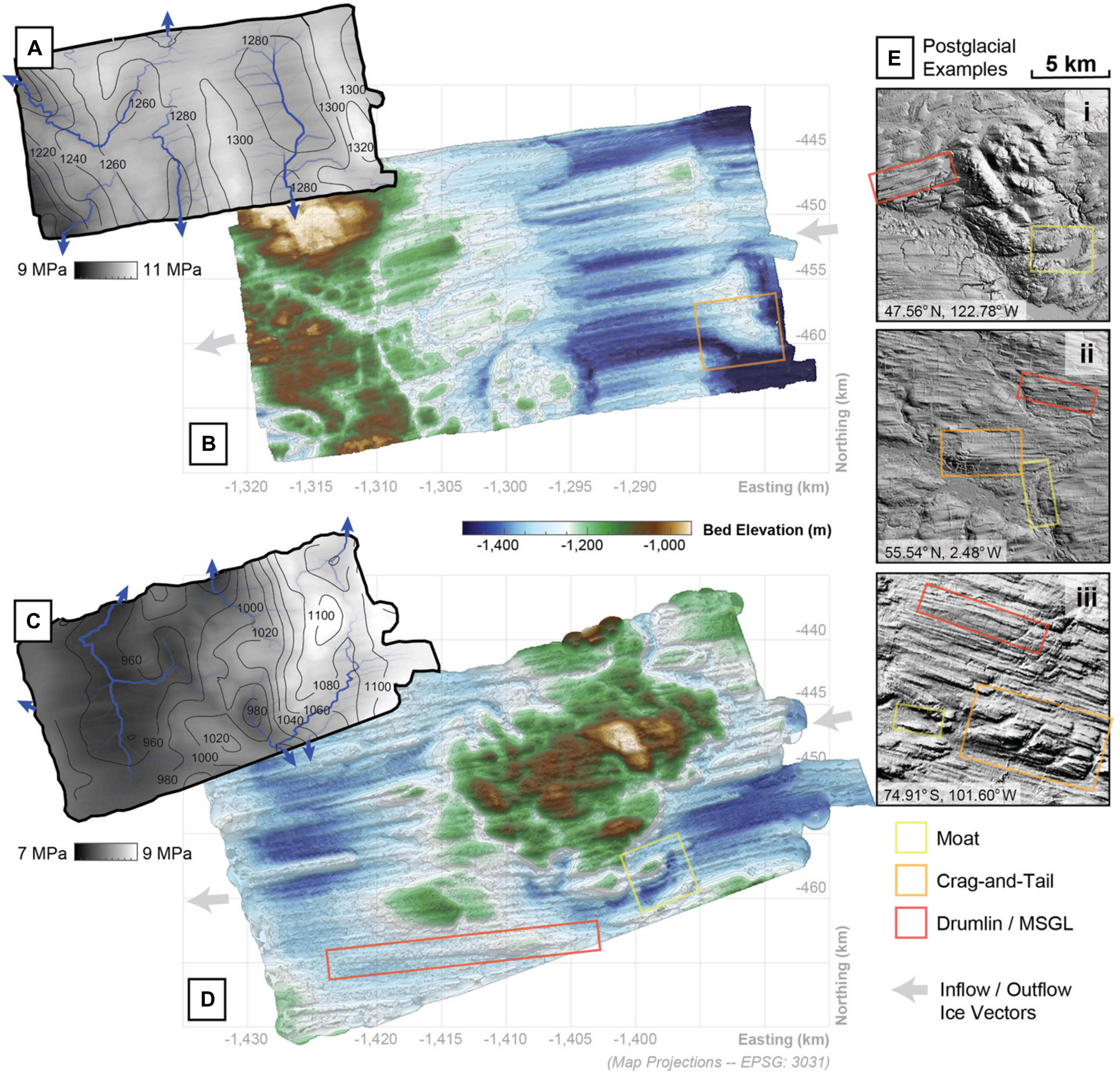

Figure 2. (A,C) Glaciological context of our Thwaites Glacier, West Antarctica, radar surveys, including surface elevation (Howat et al., 2019) (20 m contours), glaciostatic hydraulic potential (grayscale image), and preferred water flow pathways (blue traces, with intensity scaled by catchment area). (B,D) Fine-resolution bed topographies derived from swath radar. Features visible in these radar maps are directly comparable to landforms observed in formerly glaciated terranes (E; i: Washington State, USA [https://lidarportal.dnr.wa.gov/#47.85003:-122.91504:7]; ii: UK [Hughes et al., 2010]; iii: continental shelf, West Antarctica [Nitsche et al., 2013]). MSGL—megascale glacial lineation.

These models combine observable (or inferable) ice-flow parameters with often-unknown, but assumed-to-be-uniform, physical parameters (such as till grain size, deforming till depth, sediment transport diffusivity, and ice rheology scalers) to predict lineation morphology. We focus on variations in lineation length and width with basal shear stress (Joughin et al., 2014, 2006) and ice velocity (Mouginot et al., 2019), which set the optimal scale for bedform growth across these models. The morphological statistics from our surveys, together with data from Rutford Ice Stream (King et al., 2009, 2016—the most complete high-resolution survey outside this study), are presented in Figure 3.

Two characteristics of lineation formation are apparent: (1) there is no clear relationship between flow speed and lineation morphology, while basal shear stress appears to be weakly correlated with lineation morphology; and (2) observed trends in MSGL width as a function of basal shear stress follow the opposite trend of predictions from spiral ice flows and subglacial hydrologic erosion.

Inconsistencies with published instability models strengthen the argument for either multiple formation mechanisms or a primary dependence on preexisting geology. While the relationship between basal shear stress and MSGL morphology cannot directly confirm any existing model, it does provide a way to evaluate qualitative differences in other proposed models.

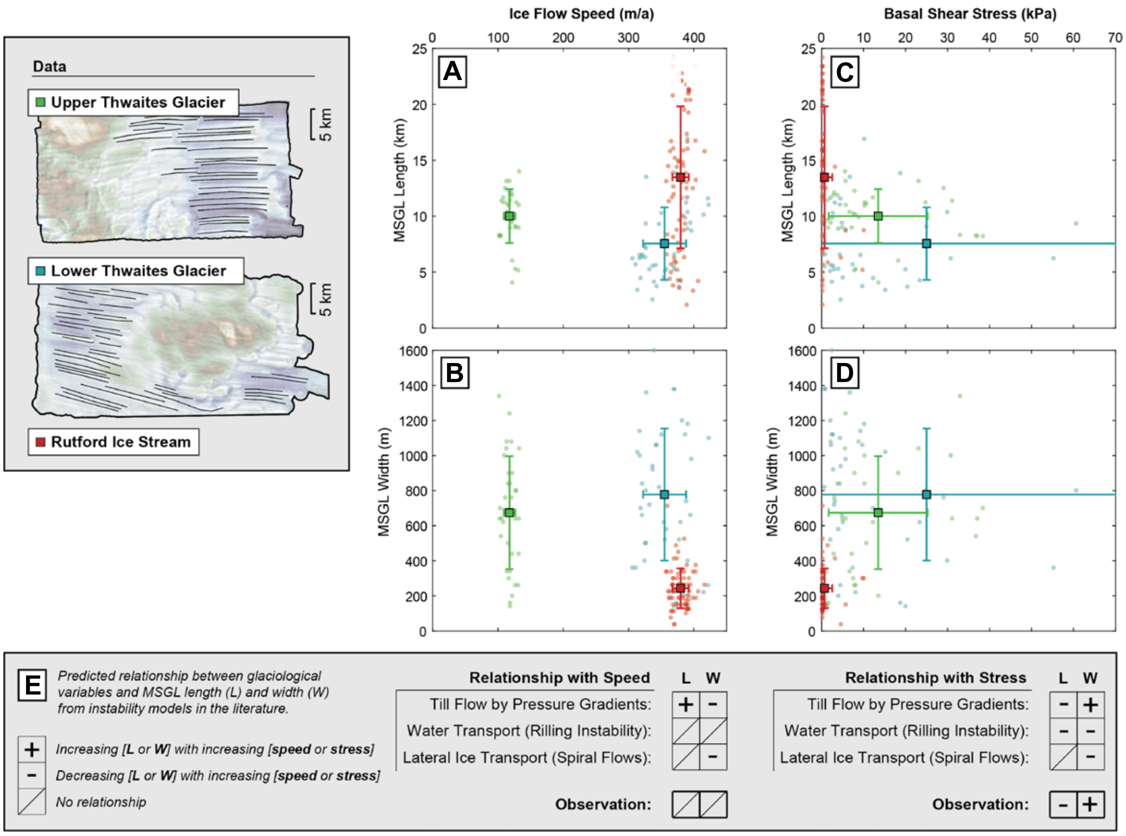

Figure 3. Average morphological characteristics of subglacial bedforms plotted against ice-flow velocity (A,B) and basal shear stress inferred from ice-flow models (Joughin et al., 2014, 2006) (C,D; including ± 1σ distributions). Thwaites Glacier and Rutford Ice Stream are in West Antarctica. MSGL—megascale glacial lineation. We present the value corresponding to the downstream bedform termination (where glaciological variables theoretically limit their size). (E) Model predictions of bedform shape.

EVIDENCE FOR THE ROLES OF ICE AND WATER

High basal shear stresses often imply low subglacial water pressure (Lliboutry, 1987). Thus, our observation that basal shear stress and MSGL morphology are weakly correlated could indicate that glaciers with a more highly pressurized basal water system foster increased lineation length and narrower width. If this were due to direct sediment transport by water, bedforms that originate from an unsculpted subglacial landscape should form parallel to the dominant regional hydraulic gradients.

Ice at Thwaites Glacier is forced to stretch and thin as it flows over large subglacial ridges, leading to reverse ice-surface gradients that act as hydrologic baffles along flow (Figs. 2A and 2C; see the Data Repository for hydraulic gradient calculations). Thus, regional subglacial hydrologic catchments run perpendicular to the ice-flow direction. Lineations here are primarily parallel to the ice flow direction, implying that till transport by ice (and not bedload transport in subglacial streams) must initiate the lateral troughs adjacent to observed lineations. Existing hydraulic gradients are, however, consistent with the orientation of moats, indicating water-driven erosion of the bed could be involved in their formation. Where MSGL orientation differs from the ice flow direction, the MSGLs curve around major obstacles to flow, indicating that either (1) MSGLs can form oblique to ice flow where till-transport down slope dominates over till transport over obstacles, (2) the basal ice flow direction differs from the surface flow direction in the presence of large subglacial obstacles, or (3) MSGLs can preserve evidence of non-steadiness in the ice flow direction.

Preexisting heterogeneity in the subglacial till properties, most notably porosity (Boulton, 1987), likely drives the formation of incipient bedforms. As bedforms grow, their interaction with ice would modify subglacial pressure gradients at the scale of the bedform, and reinforce bedform growth by water redistribution. Local variations in effective stress (which control till entrainment in basal ice), in part governed by hydrology and in part by form drag, must alter the coupling between ice and sediment, modifying the pattern and net balance between erosion and deposition of sediment that occurs in the pressure field induced by the bedforms. This agrees conceptually with the model by Iverson et al. (2017); however, several of the characteristics they use to explain drumlins at Iceland's Múlajökull glacier (channelized water flow, high effective stress) are unlikely in the lineation fields under Thwaites Glacier. In addition, our observations agree qualitatively with till flow models that explain MSGL formation using lee-side pressure lows (Barchyn et al., 2016), but quantitative disagreement remains in the size of predicted bedforms across all models.

CONCLUSIONS

Existing models that describe drumlins and MSGLs as emergent, forming from an inherent instability at the bed, are unable to explain the variations in MSGL morphology observed *in situ* under West Antarctic ice streams. MSGL orientation appears related to local ice flow direction, but unrelated to regional water flow direction, implying that the direct transport of sediment by ice controls bedform initation here. Thwaites Glacier flows across regularly spaced, large ridges (potentially fault-block topography), which may limit MSGL length. Ultimately, MSGL size in these surveys is not uniquely correlated with any single glaciological variable, but MSGL length increases weakly with reduced basal shear stress and inferred high basal water pressure.

Swath radar represents a major improvement over conventional radar depth sounding. But it is not a panacea for the challenges of mapping ice thickness over the millions of square kilometers required to fully resolve the Antarctic and Greenland ice sheets. With swath widths of only a few kilometers, typical radar survey geometries (with line spacings ≥5 km) would still yield incomplete coverage and be subject to data degradation by interpolation and down-sampling. What swath radar does provide is image resolution parity in the along- and across-track directions. This allows for robust morphometric interpretation without interpolation errors and missing information between lines; makes it possible to collect along-flow data (for englacial layer interpretation; e.g., Holschuh et al., 2017) while capturing cross-flow subglacial roughness; and enables targeted, high-density surveys over sensitive areas such as grounding lines to provide seamless topographies for use in ice sheet models.

Qualitative differences between post-glacial landscapes and those observed *in situ* in West Antarctica require further study. *In situ* lineations tend to be much larger than those measured in post-glacial landscapes (Spagnolo et al., 2014). This difference could be due to biased sampling of *in situ* data; assuming the reorganization time scale for bedforms is short (as has been inferred by Boulton [1987] and Smith et al. [2007]), features mapped in post-glacial landscapes preferentially sample glacier conditions of the near-terminus as the glacier retreats past them. Future swath radar data have the potential to resolve this discrepancy, identify differences in bedforms for marine- and land-terminating ice streams, and separate late-stage glacier modification from post-glacial reworking.

ACKNOWLEDGMENTS

We thank the three anonymous reviewers, as well as colleagues at the International Glaciological Symposium on Erosion and Deposition, for their comments that led to a much stronger manuscript. Funding for data collection and analysis was provided by the National Science Foundation (grants NSF0424589 and NSF1738934) and NASA (NNX16AM01G).

REFERENCES CITED

Al-Ibadi, M., et al., 2017, DEM extraction of the basal topography of the Canadian archipelago ICE caps via 2D automated layer-tracker: International Geoscience and Remote Sensing Symposium (IGARSS), p. 965–968, https://doi.org/10.1109/IGARSS.2017.8127114.

Atkinson, N., Utting, D.J., and Pawley, S.M., 2014, Landform signature of the laurentide and cordilleran ice sheets across Alberta during the last glaciation: Canadian Journal of Earth Sciences, v. 51, p. 1067–1083, https://doi.org/10.1139/cjes-2014-0112.

Barchyn, T.E., Dowling, T.P.F., Stokes, C.R., and Hugenholtz, C.H., 2016, Subglacial bed form morphology controlled by ice speed and sediment thickness: Geophysical Research Letters, v. 43, p. 7572–7580, https://doi.org/10.1002/2016GL069558.

Benediktsson, Í.Ö., Jónsson, S.A., Schomacker, A., Johnson, M.D., Ingólfsson, Ó., Zoet, L., Iverson, N.R., and Stötter, J., 2016, Progressive formation of modern drumlins at Múlajökull, Iceland: Stratigraphical and morphological evidence: Boreas, v. 45, p. 567–583, https://doi.org/10.1111/bor.12195.

Benn, D.I., and Evans, D.J.A., 2010, Glaciers and Glaciation: Abingdon, UK, Routledge, 816 p.

Bingham, R.G., et al., 2017, Diverse landscapes beneath Pine Island Glacier in fluence ice flow: Nature Communications, v. 8, p. 1–9, https://doi.org/10.1038/s41467-017-01597-y.

Boulton, G.S., 1987, A theory of drumlin formation by subglacial sediment deformation, *in* Menzies, J. and Rose, J. eds., Drumlin Symposium: Rotterdam, Belkema, p. 25–80.

Clark, C.D., Ely, J.C., Spagnolo, M., Hahn, U., Hughes, A.L.C., and Stokes, C.R., 2018, Spatial organization of drumlins: Earth Surface Processes and Landforms, v. 43, p. 499–513, https://doi.org/10.1002/esp.4192.

Ely, J.C., Clark, C.D., Spagnolo, M., Stokes, C.R., Greenwood, S.L., Hughes, A.L.C., Dunlop, P., and Hess, D., 2016, Do subglacial bedforms comprise a size and shape continuum?: Geomorphology, v. 257, p. 108–119, https://doi.org/10.1016/j.geomorph.2016.01.001.

Fowler, A.C., 2010, The formation of subglacial streams and mega-scale glacial lineations: Proceedings of the Royal Society: Mathematical, Physical and Engineering Sciences, v. 466, p. 3181–3201, https://doi.org/10.1098/rspa.2010.0009.

Fowler, A.C., 2018, The philosopher in the kitchen: The role of mathematical modelling in explaining drumlin formation: GFF, v. 140, p. 93–105, https://doi.org/10.1080/11035897.2018.1444671.

Hättestrand, C., and Clark, C.D., 2006, The glacial geomorphology of Kola Peninsula and adjacent areas in the Murmansk Region, Russia: Journal of Maps, v. 2, p. 30–42, https://doi.org/10.4113/jom.2006.41.

Hindmarsh, R.C.A., 1998, Drumlinization and drumlin-forming instabilities: Viscous till mechanisms: Journal of Glaciology, v. 44, p. 293–314, https://doi.org/10.1017/S002214300000263X.

Holschuh, N., Parizek, B.R., Alley, R.B., and Anandakrishnan, S., 2017, Decoding ice sheet behavior using englacial layer slopes: Geophysical Research Letters, v. 44, p. 5561–5570, https://doi.org/10.1002/2017GL073417.

Howat, I.M., Porter, C.C., Smith, B.E., Noh, M.-J., and Morin, P.J., 2019, The reference elevation model of Antarctica: The Cryosphere, v. 13, p. 665–674, https://doi.org/10.5194/tc-13-665-2019.

Hughes, A.L.C., Clark, C.D., and Jordan, C.J., 2010, Subglacial bedforms of the last British Ice sheet: Journal of Maps, v. 6, p. 543–563, https://doi.org/10.4113/jom.2010.1111.

Iverson, N.R., McCracken, R.G., Zoet, L.K., Benediktsson, I.O., Schomacker, A., Johnson, M.D., and Woodard, J., 2017, A theoretical model of drumlin formation based on observations at Múlajökull, Iceland: Journal of Geophysical Research: Earth Surface, v. 122, p. 2302–2323, https://doi.org/10.1002/2017JF004354.

Ives, L.R.W., and Iverson, N.R., 2019, Genesis of glacial flutes inferred from observations at Múlajökull, Iceland: Geology, v. 47, p. 387–390, https://doi.org/10.1130/G45714.1.

Jezek, K., Wu, X., Gogineni, P., Rodríguez, E., Freeman, A., Rodriguez-Morales, F., and Clark, C.D., 2011, Radar images of the bed of the Greenland Ice Sheet: Geophysical Research Letters, v. 38, p. 1–5, https://doi.org/10.1029/2010GL045519.

Joughin, I., Bamber, J.L., Scambos, T., Tulaczyk, S., Fahnestock, M., and MacAyeal, D.R., 2006, Integrating satellite observations with modelling: Basal shear stress of the Filcher-Ronne ice streams, Antarctica: Philosophical Transactions of the Royal Society: A, Mathematical, Physical and Engineering Sciences, v. 364, p. 1795–1814, https://doi.org/10.1098/rsta.2006.1799.

Joughin, I., Smith, B.E., and Medley, B., 2014, Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica: Science, v. 344, p. 735–738, https://doi.org/10.1126/science.1249055.

King, E.C., Hindmarsh, R.C.A., and Stokes, C.R., 2009, Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream: Nature Geoscience, v. 2, p. 585–588, https://doi.org/10.1038/ngeo581.

King, E.C., Pritchard, H.D., and Smith, A.M., 2016, Subglacial landforms beneath Rutford Ice Stream, Antarctica: Detailed bed topography from ice-penetrating radar: Earth System Science Data, v. 8, p. 151–158, https://doi.org/10.5194/essd-8-151-2016.

Nitsche, F.O., Gohl, K., Larter, R.D., Hillenbrand, C.-D., Kuhn, G., Smith, J.A., Jacobs, S., Anderson, J.B., and Jakobsson, M., 2013, Paleo ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica: The Cryosphere, v. 7, p. 249–262, https://doi.org/10.5194/tc-7-249-2013.

Lliboutry, L., 1987, Realistic, yet simple bottom boundary conditions for glaciers and ice sheets: Journal of Geophysical Research, v. 92, p. 9101–9109, https://doi.org/10.1029/JB092iB09p09101.

Mouginot, J., Rignot, E., and Scheuchl, B., 2019, Continent-wide, interferometric SAR phase, Mapping of Antarctic ice velocity: Geophysical Research Letters, v. 46, p. 9710–9718, https://doi.org/10.1029/2019GL083826.

Muto, A., Anandakrishnan, S., Alley, R.B., Horgan, H.J., Parizek, B.R., Koellner, S., Christianson, K., and Holschuh, N., 2019, Relating bed character and subglacial morphology using seismic data from Thwaites Glacier, West Antarctica: Earth and Planetary Science Letters, v. 507, p. 199–206, https://doi.org/10.1016/j.epsl.2018.12.008.

Napieralski, J., and Nalepa, N., 2010, The application of control charts to determine the effect of grid cell size on landform morphometry: Computers & Geosciences, v. 36, p. 222–230, https://doi.org/10.1016/j.cageo.2009.06.003.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., and Morris, P., 2002, Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf: Geophysical Research Letters, v. 29, p. 41-1–41-4, https://doi.org/10.1029/2001GL014488.

Paden, J., Akins, T., Dunson, D., Allen, C., and Gogineni, P., 2010, Ice-sheet bed 3-D tomography: Journal of Glaciology, v. 56, p. 3–11, https://doi.org/10.3189/002214310791190811.

Rodríguez-Morales, F., et al., 2013, Advanced multifrequency radar instrumentation for polar research: IEEE Transactions on Geoscience and Remote Sensing, v. 52, p. 1–19, https://doi.org/10.1109/TGRS.2013.2266415.

Schoof, C., 2007, Pressure-dependent viscosity and interfacial instability in coupled ice-sediment flow: Journal of Fluid Mechanics, v. 570, p. 227–252, https://doi.org/10.1017/S0022112006002874.

Schoof, C.G., and Clarke, G.K.C., 2008, A model for spiral flows in basal ice and the formation of subglacial flutes based on a Reiner-Rivlin rheology for glacial ice: Journal of Geophysical Research: Solid Earth, v. 113, p. 1–12, https://doi.org/10.1029/2007JB004957.

Smith, A.M., and Murray, T., 2009, Bedform topography and basal conditions beneath a fast-flowing West Antarctic ice stream: Quaternary Science Reviews, v. 28, p. 584–596, https://doi.org/10.1016/j.quascirev.2008.05.010.

Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Adalgeirsdóttir, G., Behar, A.E., and Vaughan, D.G., 2007, Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream: Geology, v. 35, p. 127–130, https://doi.org/10.1130/G23036A.1.

Spagnolo, M., Clark, C.D., Ely, J.C., Stokes, C.R., Anderson, J.B., Andreassen, K., Graham, A.G.C., and King, E.C., 2014, Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset: Earth Surface Processes and Landforms, v. 39, p. 1432–1448, https://doi.org/10.1002/esp.3532.

Stokes, C.R., Spagnolo, M., and Clark, C.D., 2011, The composition and internal structure of drumlins: Complexity, commonality, and implications for a unifying theory of their formation: Earth-Science Reviews, v. 107, p. 398–422, https://doi.org/10.1016/j.earscirev.2011.05.001.

Printed in USA