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Corresponding author:
Richard B. Alley;
Email: rba6@psu.edu

GHOSTly flute music: drumlins, moats and the bed of Thwaites Glacier

Richard B. Alley[1], Nick Holschuh[2], Byron Parizek[1,3], Lucas K. Zoet[4], Kiya Riverman[5], Atsuhiro Muto[6], Knut Christianson[7], Elisabeth Clyne[1], Sridhar Anandakrishnan[1] and Nathan T. Stevens[1]

[1]Department of Geosciences, and Earth and Environmental Systems Institute, Pennsylvania State University, University Park, PA, USA; [2]Department of Geology, Amherst College, Amherst, MA, USA; [3]Mathematics and Geoscience, Pennsylvania State University, Dubois, PA, USA; [4]Department of Geoscience, University of Wisconsin, Madison, WI, USA; [5]Department of Environmental Studies, University of Portland, Portland, OR, USA; [6]Department of Earth and Environmental Science, Temple University, Philadelphia, PA, USA and [7]Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA

Abstract

Glacier-bed characteristics that are poorly known and modeled are important in projected sea-level rise from ice-sheet changes under strong warming, especially in the Thwaites Glacier drainage of West Antarctica. Ocean warming may induce ice-shelf thinning or loss, or thinning of ice in estuarine zones, reducing backstress on grounded ice. Models indicate that, in response, more-nearly-plastic beds favor faster ice loss by causing larger flow acceleration, but more-nearly-viscous beds favor localized near-coastal thinning that could speed grounding-zone retreat into interior basins where marine-ice-sheet instability or cliff instability could develop and cause very rapid ice loss. Interpretation of available data indicates that the bed is spatially mosaicked, with both viscous and plastic regions. Flow against bedrock topography removes plastic lubricating tills, exposing bedrock that is eroded on up-glacier sides of obstacles to form moats with exposed bedrock tails extending downglacier adjacent to lee-side soft-till bedforms. Flow against topography also generates high-ice-pressure zones that prevent inflow of lubricating water over distances that scale with the obstacle size. Extending existing observations to sufficiently large regions, and developing models assimilating such data at the appropriate scale, present large, important research challenges that must be met to reliably project future forced sea-level rise.

Introduction

Thwaites Glacier is the most-likely path from modern ice sheets for large, rapid loss of grounded ice leading to sea-level rise (e.g. Scambos and others, 2017; DeConto and others, 2021). At present, ice in the grounding zone is typically ~500 m thick, but retreat into interior basins could increase the grounding-zone thickness several-fold, allowing much faster ice discharge, with further retreat likely through the marine-ice-sheet instability. Thwaites Glacier flows through an outlet that is exceptionally wide among ice streams, but that is relatively narrow compared to the several-fold wider front that could develop during retreat. An outlet both much wider and thicker would have much greater ice discharge leading to sea-level rise. Furthermore, if Thwaites Glacier loses its ice shelf and retreats into interior basins, the evolving calving front would become higher and wider than any now existing on Earth. Highly uniform, fine-grained ice could support tall cliffs (e.g. Hanson and Hooke, 2003; Clerc and others, 2019), but such ice does not exist in large volumes in actual ice sheets, where many types of inhomogeneities and damage are likely to limit subaerial cliffs to values not much taller than 100 m (Bassis and Walker, 2012; Parizek and others, 2019; see review by Alley and others, 2023), especially if there is meltwater wedging open surface crevasses (Pollard and others, 2015). Cliff failure could then drive sea-level rise at unprecedented rates.

Large, rapid sea-level rise might be avoided if ice shelves persist or if the now-retreating grounding zone stabilizes before retreating from the modern ‘bottleneck’ with its relatively narrow, shallow outlet on a bed that is not generally deepening inland (Fig. 1). Ice-shelf persistence or loss involves a wide range of important issues (reviewed by, e.g. Scambos and others, 2017 and Alley and others, 2023), some of which affect the grounding-zone stress balance and thus the likelihood or rate of grounding-zone retreat. Retreat also depends on many stabilizing and destabilizing factors; forcing by reduction or loss of ice-shelf backstress and melting from warmer waters circulating in grounding-zone estuaries (Horgan and others, 2013) may be especially important.

Basal ‘sliding law’

Even if ice-shelf and grounding-zone processes were well-known and modeled accurately, great uncertainty is attached to the internal and basal ice-flow response. Changes in internal deformation of the ice are important, with significant uncertainties, but the largest issues arise from uncertainties about changing basal motion of the ice.

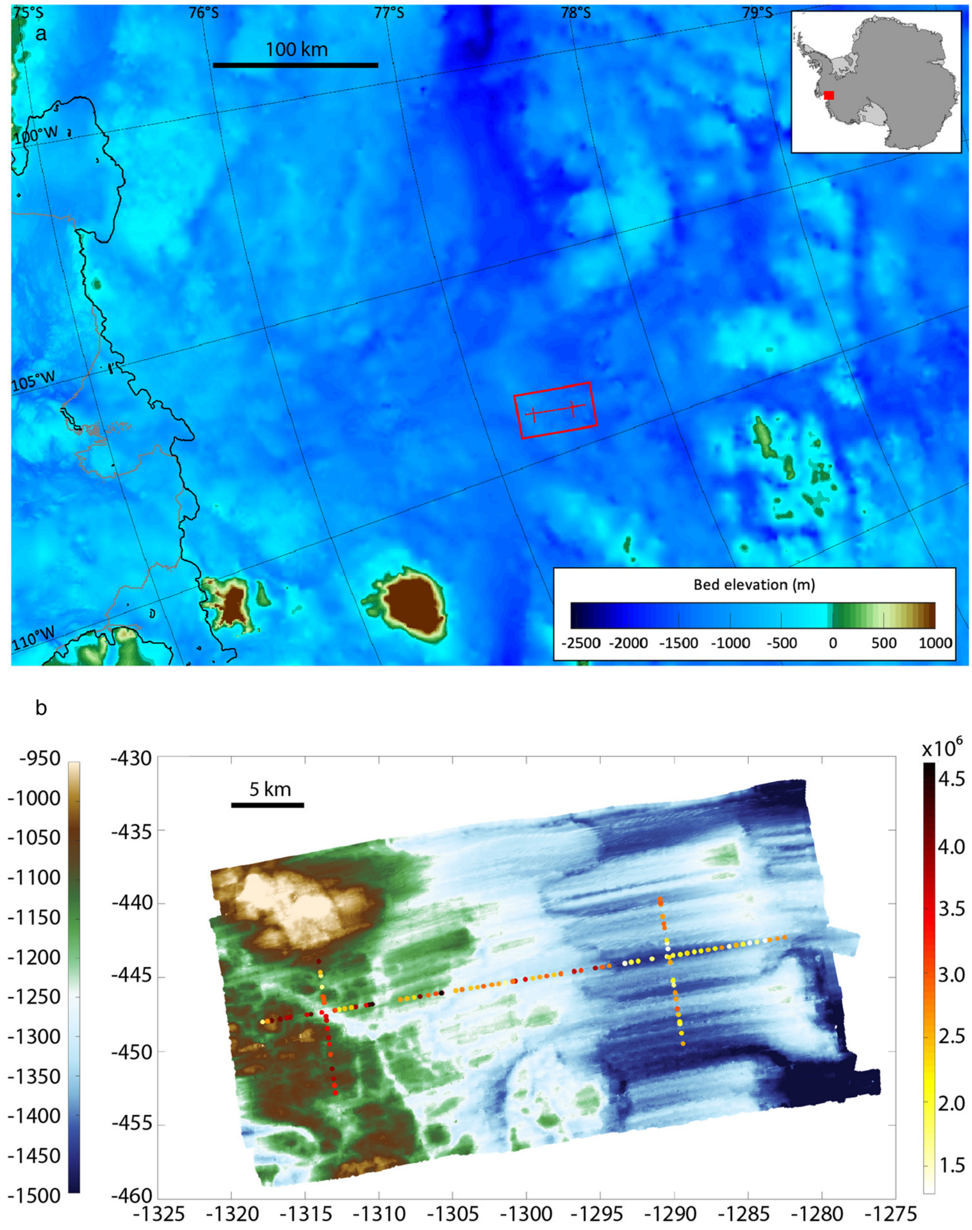

Figure 1. Key features of the bed of Thwaites Glacier. (a). Bed elevation from BedMachine Antarctica version 2 (Morlighem, 2020), with elevation indicated by color scale, ice-shelf front (gray), and grounding line (black), with survey location and seismic lines in red. Thwaites discharges primarily between ~109 and 104 W longitude, across a relatively shallow grounding zone. (b). Bed of the up-glacier part of Thwaites Glacier (Holschuh and others, 2020), with elevation (left color bar, m; note that scale differs from 1a, as indicated) from airborne swath radar, and acoustic impedance (right color bar, kg m^{-2} s^{-1}) from seismic surveys (Muto and others, 2019*a*, 2019*b*). Lower acoustic impedance indicates softer bed (deforming tills), and higher acoustic impedance indicates harder bed (bedrock). Holschuh and other (2020) and Alley and others (2021) provide additional, annotated data on the bed character. Radar data and gridded topographies are accessible through the University of Washington ResearchWorks Archive (http://hdl.handle.net/1773/44950).

Basal motion is often represented in models by a ‘sliding law’. Importantly, this is neither a law, nor truly sliding in many cases (e.g. Cuffey and Paterson, 2010, ch. 7). The ‘law’ is a parameterization of important contributions to velocity from processes in debris-laden basal ice, between that ice and bedrock or till, and within till. The ‘law’ must represent ice motion over a wide range of topographic features and a mosaic of bed types involving both till and bedrock. Many of these features are large enough to be resolved in geophysical surveys and models, but smaller features require parameterizations (Hoffman and others, 2022). We will refer to sliding laws here for simplicity.

How the basal processes are parameterized in ice-flow models fundamentally affects the model projections. For example, in a flowline model of Thwaites Glacier, Parizek and others (2013) showed that under strong forcing, whether or not the grounding zone retreated into interior basins depended on the sliding law.

Uncertainty in the sliding law impacts most or all projections of ice-sheet and glacier change (e.g. Åkesson and others, 2021), and is illustrated clearly for the Antarctic ice sheet including Thwaites Glacier by the results of the ABUMIP model intercomparison (Antarctic BUttressing Model Intercomparison Project; Sun and others, 2020). A total of 15 models of various types, with a wide range of basal sliding laws, subjected their modeled Antarctic ice sheet to either very high sub-ice-shelf melt rates or sustained ice-shelf loss, although without the additional cliff calving that can drive the fastest sea-level rise. The forcing was applied at the start of the runs and sustained throughout, and thus notably exceeds realistic forcing, but provides an excellent way to assess the effects of model parameterizations. For the large sub-ice-shelf melt rate, response over the first model century ranged from slight ice-sheet growth to mass loss of almost 7 m of sea-level equivalent. For specified ice-shelf loss, all models showed ice-sheet shrinkage, but the range of results spanned roughly an order of magnitude after a century, again with almost 7 m of sea-level equivalent for the fastest loss. Many differences between the models were important in the disparate results, but strong dependence on the level of plasticity of the sliding law was clear (see their Figure 5 comparing sea-level rise from different models, ordered by sliding law, and Figure 6 showing results from one model with different sliding laws; Sun and others, 2020). Additional insights into the importance of the sliding law for ice-sheet response to forcing are found in many other studies, including Brondex and others (2019), Joughin and others (2019), Schwans and others (2023), and Kazmierczak and others (2022).

Sliding laws are often formulated such that basal velocity increases with basal shear stress raised to some power, which may range from 1 (linear-viscous) to approaching infinite (more-nearly plastic, perhaps with zero motion specified for shear stress below some shear strength), or perhaps some combination such as linear-viscous motion for low shear stresses but plastic or frictional motion for stress above some 'Iken limit', the maximum shear stress that the bed can support (see, e.g. Budd and others, 1979; Iken, 1981; Cuffey and Paterson, 2010; Helanow and others, 2021). At low stresses, viscous laws tend to produce faster sliding than plastic laws, but deformation in the ice column generally dominates mass flux for both parameterizations in central regions of ice sheets with low stresses. (For simplicity, we will refer to the end-member viscous and plastic laws.) Where sliding is dominant, plastic laws give larger velocity changes for shear-stress perturbations; this means that reduction in ice-shelf buttressing causes significant flow acceleration in the grounding zone but minimal thinning there, with the faster flow propagating well inland (Parizek and others, 2013). In contrast, for viscous behavior, most of the response to loss of ice-shelf buttressing is localized in the grounding zone, giving relatively little acceleration well inland but favoring grounding-zone thinning that speeds retreat from the stabilizing sill. For models lacking cliff calving, the plastic behavior tends to give larger sea-level rise in response to reduced buttressing as in the ABUMIP experiments; however, if retreat from the sill is followed by ice-shelf loss and then very rapid cliff calving, a viscous bed might drive larger sea-level rise (Pollard and others, 2015; DeConto and others, 2021).

Sliding laws often include dependence on the basal water system. Frozen-bedded glaciers lacking a water system have very low basal velocity. For melted beds with basal water, the sliding velocity tends to increase with water supply up to some limit, beyond which efficient channelization of flow can partially drain the bed and cause decrease of basal velocity with increasing water supply (Cuffey and Paterson, 2010). In the inefficient drainage regime, which likely applies to most of the area of the beds of ice sheets (e.g. Alley and others, 1997), additional water supply tends to raise the water pressure, growing water-filled cavities that separate ice from bed and thus facilitate sliding, and weakening tills by supporting more of the overburden pressure that otherwise tends to interlock grains so they cannot move past each other. Some ice-flow models include, or can include, such a dependence of basal velocity on the basal water system, although only one of the ABUMIP models included a water-pressure-dependent sliding law (Kazmierczak and others (2022) provide additional insights to the importance of the water system to the ABUMIP-type experiments).

Extensive evidence (reviewed in, e.g. Alley and others, 1997) shows that thawed till beds generally deform, and exhibit more-nearly-plastic behavior. Hard beds almost surely have a more-nearly-viscous behavior under at least many conditions, although the recent emphasis on the possibility that ice deformation depends on the fourth power of stress rather than the third (Millstein and others, 2022) may recommend testing a higher power in models, with potential consequences (see Sun and others, 2020, Fig. 5). Models that experience an 'Iken limit' typically have been formulated assuming that the ice interacting with rigid bedrock lacks debris, and thus ignoring the dynamic (skin) drag from the widespread to ubiquitous occurrence of debris in basal ice, which may raise the limit or avoid it entirely (see, e.g. Zoet and others, 2020; Helanow and others, 2021).

Importantly, extensive observations of deglaciated beds and beneath modern glaciers and ice sheets, including beneath Thwaites Glacier as summarized briefly below, show that the basal character is highly variable spatially in ways that will cause spatial variations in the sliding law. Models, however, almost never use a spatially varying basal sliding law that is registered to the real bed of the glacier to reflect the observed variations in bed type. Omitting plastic regions may induce only small error if they are always exceptionally well lubricated and thus unimportant in the force balance, but otherwise, models lacking this spatial information must be missing aspects of the actual behavior. Koellner and others (2019) conducted idealized flowline experiments forced from the downglacier end for domains in which spatially varying sliding laws were draped over basal topography, and found that while under many conditions the mixed bed produced behaviors that were intermediate between the end-member beds, under some conditions the mixed bed produced more-extreme behavior than either end-member. This is just one set of model experiments, but suggests the need to accurately represent the true bed with its appropriate sliding laws and their spatial extent, a task that will not be easy (see below).

Insights to the bed

Three-dimensional maps of large areas of ice-sheet beds generally have neither sufficient detail to resolve the main bedforms (e.g. the moats and the drumlins or flutes observed beneath Thwaites Glacier; see below), nor supporting geophysical data to characterize the nature of the bed (whether bedrock, till or other materials) or to characterize the water system. Some data with such resolution are available. Here, we focus especially on results of CReSIS surveys of the inland regions of Thwaites Glacier (Fig. 1a) (Muto and others, 2019*a*, 2019*b*; Clyne and others, 2020; Holschuh and others, 2020, as summarized by Alley and others, 2021), together with data from Rutford Ice Stream (Smith and others, 2007) and Whillans Ice Stream (Barcheck and others, 2020).

The map in Figure 1b shows the bed of Thwaites Glacier as surveyed by airborne swath radar (Holschuh and others, 2020), with seismic data draped over it. As reviewed by Alley and others (2021), much of the West Antarctic ice sheet occupies the extended crust of the West Antarctic Rift System, with the Transantarctic Mountains as one rift flank, and Marie Byrd Land and other highlands as the other rift flank. Flow is preferentially directed along the fault-block topography, as on the Siple Coast, but the distance from the center of the ice sheet to the front of the Ross Ice Shelf is quite long, and was even longer when the ice was advanced at glacial maxima. This caused ice to build up in central regions, driving flow across the tectonic fabric and out the gap at Thwaites Glacier. While ice flow across topography occurs frequently in many environments, such flow is probably better developed for Thwaites Glacier than for most or all other regions.

Although additional geophysical confirmation would be helpful, the linear topographic features shown in Figure 1 oriented across flow are likely the normal faults of the rift system, with upthrown blocks on the downglacier sides. The ~100-m-high flutes in the lee of the higher parts of the upthrown blocks (the tails of crag-and-tail features) are seismically thick, soft till, which thus is at least a few meters thick and perhaps much more, as seismically observed internal structures are scarce or absent. The up-glacier-facing parts of these flutes, and of shorter features that might be called drumlins (Holschuh and others, 2020), are seismically more rigid (or 'hard'), probably poorly or moderately lithified sedimentary rocks. Seismically hard regions extend into the moats eroded along the up-glacier sides of the bedrock obstacles, and then downglacier in the troughs between the raised flutes.

This distribution of features is to some extent repeated beneath Rutford Ice Stream, and perhaps also beneath Whillans Ice Stream. Beneath Rutford, the seismically harder regions of the bed are on up-glacier-facing noses of bedforms and in troughs between flutes. Microseismicity shows that important tangential drag (dynamic drag, as opposed to the form drag of the ice needing to get around the bumps) is supported in these hard-bedded regions (Kufner and others, 2021), likely arising from interactions between bedrock and clasts carried in basal ice (e.g. Zoet and others, 2013). Microseismicity was also observed in trough locations beneath Whillans Ice Stream (Barcheck and others, 2020), suggesting similar conditions there.

Occurrence in the Thwaites Glacier data of the large, bedrock-floored moats, incised as much as 50 m or more beneath the more-or-less planar surface up-glacier, was a special focus of the modeling in Alley and others (2021). Briefly, as shown first by Stokes (1851) and subsequently in all similar studies including those of Weertman (1957)-type sliding, the form drag of an obstacle creates a high-pressure zone on the upstream side to drive the flow divergence around the obstacle, with a coupled low-pressure zone on the downstream side. For ice flow over a bedrock knob, the high pressure is also exerted across the ice-bed interface, over a horizontal distance that scales with the obstacle size. For relatively rapid ice flow, hundreds of meters per year in the survey grid, the magnitude of this pressure perturbation caused by obstacles on their up-glacier sides is large compared to the pressure difference between the ice-overburden and the water pressure well away from the obstacle, and compared to changes in water pressure or ice-overburden pressure over similar length scales away from obstacles.

The soft beds of Thwaites Glacier are rather clearly in a regime for which increasing water pressure closer to the ice-overburden pressure tends to float the ice off the bed and reduce subglacial till deformation (Muto and others, 2019*b*; Hansen and Zoet, 2022). The zone of high ice pressure on the up-glacier side of an obstacle tends to prevent inflow of through-going subglacial water from up-glacier, which instead is routed far around the obstacle. Lack of this water then allows tighter coupling of the ice into the till in the high-pressure zone, increasing till deformational flux, and causing flux divergence that removes the till, exposing bedrock to erosion; this process acting over time likely explains the moats. The exclusion zone for throughgoing water extends to the side of an obstacle over a similar length scale, explaining the bedrock in troughs. Till transported over obstacles and deposited in lee-side positions then forms the large lee-side drumlins or flutes.

This stoss-side high-pressure behavior applies to all scales of obstacles. As described in Alley and others (2021), it likely lowers the melting point of ice up-glacier of abrading clasts in basal ice, causing heat-flow convergence that drives melting at the ice-bed interface and thus increases downward ice motion, resulting in an increase in the stress between the bed and abrading clasts within the basal ice. This stoss-side high pressure also occurs for all fixed obstacles in the bed, and contributes to deviations in water routing from paths that otherwise would be expected. Notably, though, the bed slope into a moat tends to capture basal water flow; learning whether moats extend far enough up-glacier and have steep enough bed slopes to offset the diversion of water away from the high-pressure region will require high-quality data and careful modeling.

Research priorities

After COVID-induced loss of field seasons and ongoing disruptions, the GHOST project (Geophysical Habitat Of Subglacial Thwaites; https://thwaitesglacier.org/projects/ghost) deployed a limited field season in 2022–2023 to collect new data to extend the high-resolution geophysical datasets noted above along and across larger regions of Thwaites Glacier, and to assess spatial occurrence of microearthquakes, although with major COVID-forced reductions in the planned program. One goal of this work is to test the hypothesis that this template is widespread: that bedrock is exposed on stoss sides of topography, and in moats with trailing troughs eroded around up-glacier sides of topographic features, with soft till in lee-side positions. Microearthquake data can be combined with results from laboratory experiments to understand the sliding law in the bedrock regions (e.g. Zoet and others, 2013, 2020). Careful surveys with targeted modeling can be used to calculate flow paths for subglacial water, and learn which downstream regions are, or are not, lubricated by water flow from up-glacier. As discussed in Alley and others (2021), the bedforms of Thwaites Glacier have experienced more-nearly steady conditions for longer times than the bedforms of most deglaciated regions, so similarities and differences may provide additional insights to formation mechanisms of bedforms.

To improve accuracy of ice-sheet projections, though, new data from Thwaites Glacier and elsewhere will need to be used in prognostic models. As noted above, whole-ice-sheet models generally are not resolving such topographic features, and so they are not applying the correct sliding laws in spatially accurate ways. Furthermore, whole-ice-sheet models generally are not routing subglacial water, with its effects on lubrication, in ways that include the pressure variations generated by flow against bedrock topography. Also, the Iken-limit sliding models may not be accurately parameterizing the frictional behavior when the effects of abrading clasts are also considered. Such detailed modeling likely is most important on the sill where Thwaites Glacier currently ends, and in the basin immediately up-glacier (e.g. Alley and others, 2019), but extending accurate modeling farther inland and ultimately to the whole ice sheet may be necessary. Modeling should address the scales at which bed types and processes need to be resolved to provide accurate projections. All of this is a huge challenge, and various intermediate models may provide guidance on the effects of including more of these processes.

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