Progressive unpinning of Thwaites Glacier from newly identified offshore ridge: Constraints from aerogravity

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[1] A new bathymetric model from the Thwaites Glacier region based on IceBridge airborne gravity data defines morphologic features that exert key controls on the evolution of the ice flow. A prominent ridge with two distinct peaks has been identified 40 km in front of the present-day grounding line, undulating between 300–700 m below sea level with an average relief of 700 m. Presently, the Thwaites ice shelf is pinned on the eastern peak. More extensive pinning in the past would have restricted flow of floating ice across the full width of the Thwaites Glacier system. At present thinning rates, ice would have lost contact with the western part of the ridge between 55–150 years ago, allowing unconfined flow of floating ice and contributing to the present-day mass imbalance of Thwaites Glacier. The bathymetric model also reveals a 1200 m deep trough beneath a bight in the grounding line where the glacier is moving the fastest. This newly defined trough marks the lowest topographic pathway to the Byrd Subglacial Basin, and the most likely path for future grounding line retreat.
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1. Introduction

[2] The glaciers flowing into Pine Island Bay drain ~20% of the West Antarctic Ice Sheet, and are collectively losing mass at a rate of 90 Gt/yr [*Rignot et al.*, 2008]. Because their beds slope downward inland [*Holt et al.*, 2006; *Vaughan et al.*, 2006] (Figure 1) these glaciers are considered to be at risk of unstable grounding line retreat and potential sites of ice sheet collapse [*Hughes*, 1981].

[3] Satellite observations since 1992 show that Pine Island Glacier has been accelerating, while Thwaites Glacier has maintained a consistently high velocity and negative mass balance, with some widening of the fast flow area [*Rignot*, 2006]. The event that triggered the Thwaites Glacier negative mass balance must have occurred prior to 1992 [*Rignot et al.*, 2008]. This difference in behavior points to the importance of local morphological controls on the glacial history of the Amundsen Sea. Knowledge of the bathymetry in front of the present-day grounding line is critical to understanding the retreat of the grounding line in the past. Operation IceBridge surveys over the area allow this bathymetry to be modeled from gravity observations for the first time.

2. Methods

[4] Operation IceBridge is a multiyear NASA project bridging the gap between ICESat missions by conducting airborne geophysical surveys in Antarctica and Greenland. One objective of IceBridge is to map previously unsurveyed regions using ice penetrating radar and gravity measurements. The data presented here were acquired by Operation IceBridge during October–November 2009.

[5] Data were acquired using the Sander Geophysics, Airborne Inertially Referenced Gravimeter (AIRGrav) on board NASA's DC8 aircraft, flying a draped survey at ~500 m above ground level [*Cochran and Bell*, 2009]. The main survey over Thwaites Glacier was flown as a series of parallel lines, 10 km apart, approximately perpendicular to the grounding line (Figure 2). Data with high horizontal accelerations due to aircraft maneuvers were excluded from the dataset. Free-air anomalies were filtered with a 70 s full wavelength filter, resulting in ~4.9 km half-wavelength resolution for a typical flying speed of 140 m/s.

[6] The ice surface elevation was measured with the NASA Airborne Topographic Mapper (ATM) laser [*Krabill*, 2009], which is capable of measuring elevations to decimeter accuracy [*Krabill et al.*, 2002]. Ice thickness was provided by a radar from the University of Kansas Center for Remote Sensing of Ice Sheets (CReSIS), the Multichannel Coherent Radar Depth Sounder (MCoRDS) [*Allen*, 2009]. Average crossover error for ice thickness measurements near the grounding line was 25 m (J. Paden, personal communication, 2011). A 1% error in the dielectric constant of ice of contributes an uncertainty of 0.5% of the total ice thickness, which is 1000 m at the grounding line. Combined radar errors across the survey region are ~30 m. As the laser and radar data were acquired on the same survey flights as the gravity data, these data are coincident in time and space, with along-track resolution equal to or better than that of the gravity survey.

[7] Bathymetry modeling from gravity was conducted in 2D along individual flight lines with Geosoft GMSys software using methods of *Talwani et al.* [1959]. A four-body forward model, of air (0 g/cm^3), ice (0.915 g/cm^3), seawater (1.028 g/cm^3) and rock (2.67 g/cm^3), was used (Figure 2c). Rock density was constrained by local geology, which comprises a crystalline basement of granodiorites and gneisses. Where homogeneous geology did not fit known bathymetric constraints, denser rock (3.0 g/cm^3) was modeled. Discrete volcanic centers that outcrop above the ice sheet in the survey area have a bimodal petrology of trachytes (2.73 g/cm^3) and basalts (~3.0 g/cm^3) [*LeMasurier*

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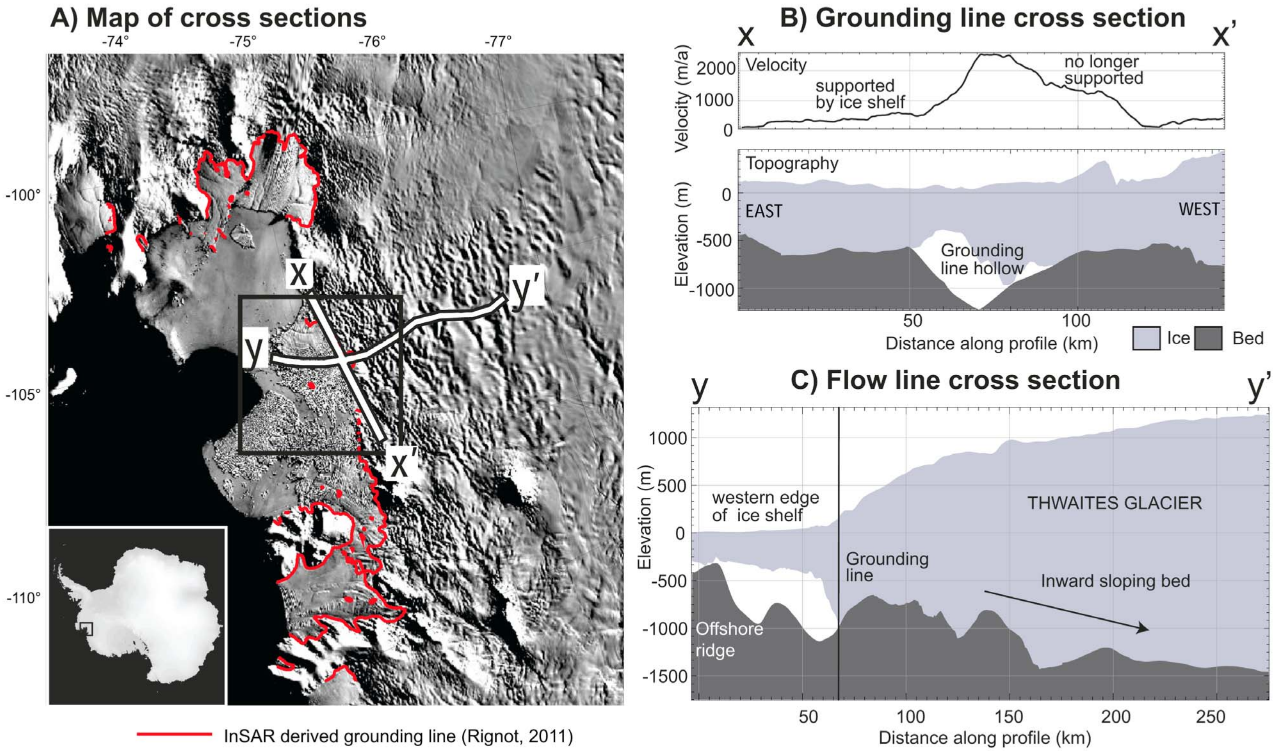

Figure 1. (a) Location of profile lines, superimposed on MODIS Mosaic of Antarctica image [*Haran et al.*, 2006], red line is 1996 grounding line of *Rignot et al.* [2011], black box shows survey area. (b) Cross section line across the grounding zone of Thwaites Glacier (x-x′). Upper profile shows velocity [*Rignot et al.*, 2008], lower profile shows ice surface, base, and bed surface. (c) Cross section line along flow line from Thwaites Glacier (y-y′).

and Thompson, 1990]. Sedimentary rocks were not included in these models, as supported by the absence of sedimentary sequences in marine seismic sections from the proximal portions of the Amundsen Sea [e.g., *Lowe and Anderson*, 2002].

[8] Ice surface and base were established by laser and radar data, respectively, each filtered to the same 70 s wavelength as the gravity data. Elevations and modeled depths are reported with respect to the WGS84 ellipsoid. The model was pinned to bathymetry known from marine surveys at the northeastern end of line 1021.16, which was used as a tie line to ensure a self-consistent model.

3. Results

3.1. Bathymetry Model and Errors

[9] The observed gravity anomaly (Figure 2b) ranges between −53 and 13 mGal. The largest anomaly is an

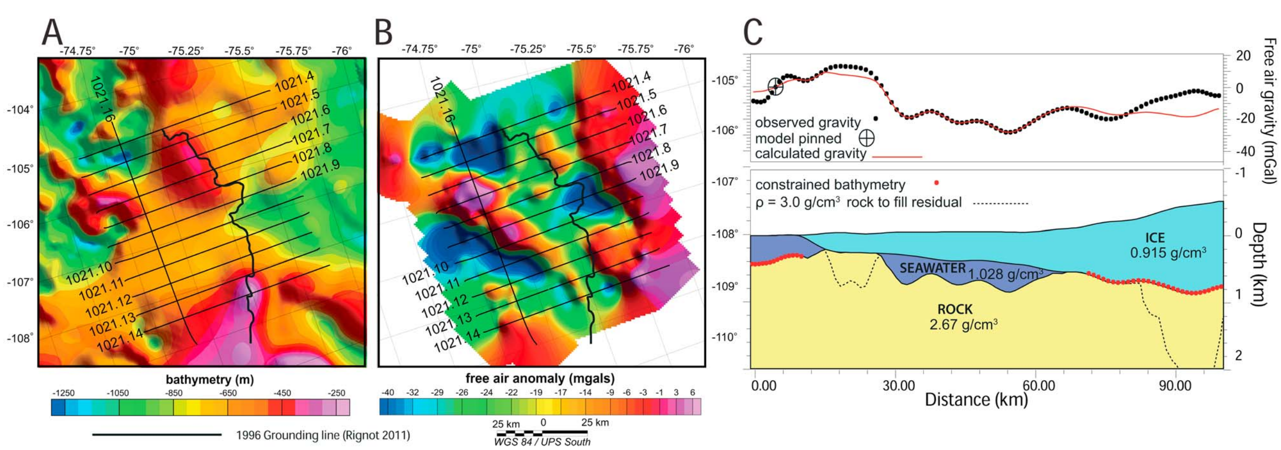

Figure 2. (a) Position of IceBridge 2009 Thwaites Glacier survey lines, superimposed on interpolated bathymetry of *Nitsche et al.* [2007]. Black line is 1996 grounding line from *Rignot et al.* [2011]. (b) Grid of free air gravity anomaly from survey. (c) The 2D model along survey line 1021.7. Calculated gravity is shown for homogeneous bedrock of density 2.67 g/cm^3. Dotted line on model shows distribution of 3.0 g/cm^3 rock required to fill residuals between calculated and observed gravity anomaly.

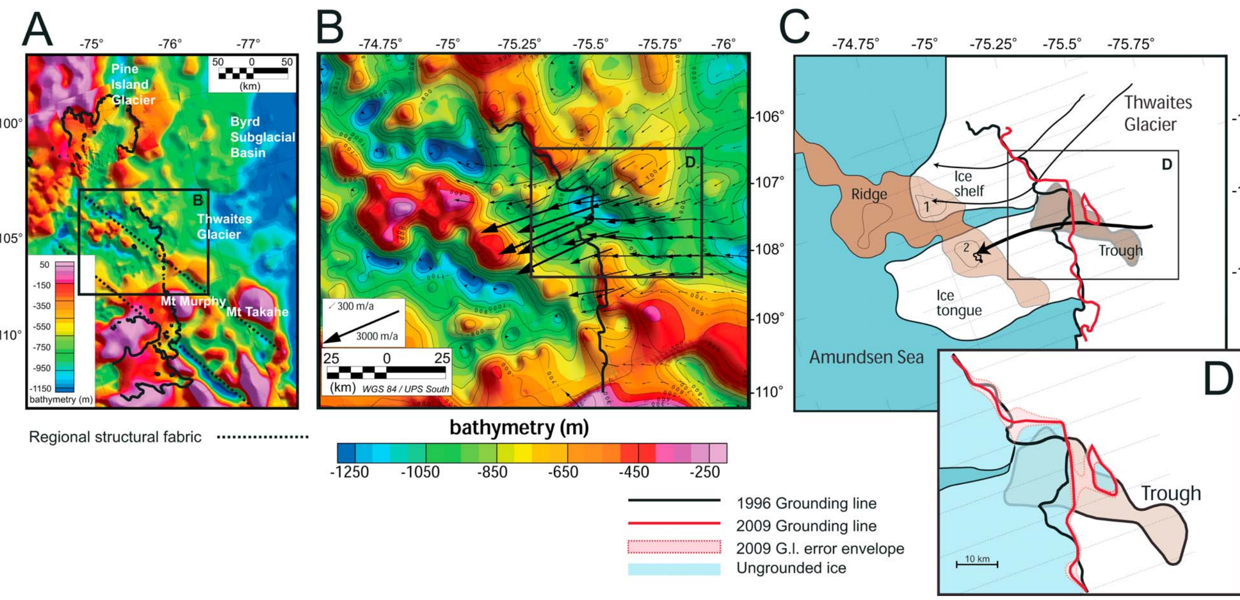

Figure 3. (a) The new bathymetry model from IceBridge data combined with bathymetry from *Nitsche et al.* [2007], *Jenkins et al.* [2010], *Holt et al.* [2006] and *Vaughan et al.* [2006]. (b) Close up of model with flow vectors from *Rignot* [2001] superimposed. (c) Cartoon of key features of the bathymetric model and flow regime. Ridge defined by 800 m depth contour, trough defined by 1000 m depth contour, 1 and 2 mark eastern and western peaks of ridge respectively. Black line is 1996 grounding line from *Rignot et al.* [2011], red line is 2009 grounding line estimated from IceBridge data. (d) Close up of grounding line at the bathymetric trough. Red zone shows error envelope of grounding line estimates, blue shows ice that is ungrounded in all estimates.

elongate gravity high with values of −16 to 13 mgal, ~40 km offshore from the present-day grounding line. A second high, ranging from −10 to 10 mgal, exists onshore of the grounding line, at the southernmost end of the survey lines.

[10] The gravity-based bathymetric model (Figure 3) has a similar shape to the observed gravity except where density differences have been included in order to fit known constraints. The bathymetric surface was constrained to always be below the base of the ice, and bed geology was considered homogeneous (density 2.67 g/cm^3) unless denser rock was required to account for residual anomalies.

[11] The prominent feature of the gravity-based bathymetric model is a 15 km wide, 700 m relief ridge trending northeast (Figure 3a). It is aligned with several other ridges identified from marine surveys [e.g., *Nitsche et al.*, 2007; *Gohl*, 2011] and the fabric revealed in the basal shear stress map of [*Joughin et al.*, 2009], but has almost twice the relief of the recently identified ridge in front of Pine Island Glacier [*Jenkins et al.*, 2010]. The ridge rises close to the ice surface at two peaks marked 1 (eastern) and 2 (western) in Figure 3c. These peaks have depths of 310 m and 430 m respectively and correspond to areas of grounded ice reported from InSAR observations from 1996 [*Rignot*, 2001]. A residual gravity anomaly over the eastern peak can be accounted for by the presence of denser rock on the ridge (Figure 2c), indicating a likely volcanic origin of these ridges. The bathymetry model also shows a trough, on the northern flank of the ridge, reaching depths of 1200 m.

[12] The southern gravity high was not reflected in bed topography from laser and radar on grounded ice, indicating a dense body in the bedrock along the present-day grounding line. Gravity lows at the southern ends of lines 1021.8, 1021.9 and 1021.10 (Figure 2b) are modeled as a deep (1200 m) trough (labeled on Figure 3c), connected to a 1000 m deep, ice filled channel leading toward the Byrd Subglacial Basin. This trough is coincident with a bight in the present-day grounding line.

[13] The error budget of a gravity based bathymetric model includes: 1) instrument errors, 2) modeling errors and 3) geologic "noise". The range of error introduced from each component of the Thwaites Glacier analysis is summarized in Table 1.

[14] 1) The instrument errors in the bathymetric model under floating ice arise from errors in the gravity measurement. Under grounded ice, errors are from the radar based ice thickness. The average crossover error for the gravity

Table 1. Summary of the Errors in the Bathymetry Model Using 2D Profiles and Assuming Minimal Variation in Geological Structure

Source	Measurement Error	Model Error	Comment
Gravimeter noise	1.67 mGal	34 m	2.67 g/cm^3 density, 600 m deep target, crossover error
Radar ice thickness	30 m		Crossover error and velocity uncertainty
Modeling error		20 m	Select pinning point to minimize residuals
Geological error	0.1 g/cm^3	10–15 m	Assuming simplest geological structure

survey is 1.7 mGal. Given the mean target depth of 600 m below sea level for the offshore ridge and an average density of 2.67 g/cm^3 this contributes an uncertainty of 34 m to the bathymetry model under floating ice. Where the ice is grounded, radar instrument errors of 30 m apply.

[15] 2) The modeling approach required a very large model space (60,000 km wide and 50 km deep) to remove the edge effects inherent in calculating the gravity effect of any body. Gravity values calculated for the model space are offset from observed values by a DC shift. The value of this shift is established by pinning the model to a point of known bathymetry. By selecting a reasonable pinning point with good marine bathymetric control the bathymetric error from the model is 20 m.

[16] 3) Based on exposures of high density rocks in the Thwaites Glacier region and the absence of sediments in the marine surveys in the Amundsen Sea, the bathymetric model is based on a single density for the bedrock (2.67 g/cm^3). Varying the basement density by 0.1 g/cm^3 varies the bathymetry model by 10–15 m. High points in the model are the least sensitive to this error as the model is pinned at gravity highs. Errors given here are stated within the assumption of minimizing geological variation. Greater density variations due to geological structure are possible but cannot be identified from current constraints.

[17] Using the modeling approach described here, and within these stated assumptions, the combined uncertainty for the gravity based bathymetric model is ±70 m.

3.2. Grounding Line Estimate and Errors

[18] The 2009 grounding configuration is estimated by comparing Operation IceBridge laser surface altimetry with predicted freeboard from radar ice thickness, assuming hydrostatic equilibrium for floating ice. Using the same densities as a similar study from the region (1.0275 g/cm^3 and 0.9 g/cm^3 [*Rignot et al.*, 2004]), little change is seen between 1996 and 2009 grounding lines where the grounding line rests on a topographic high. In contrast, at the bathymetric trough, and coincident with the bight in the grounding line, the center of the glacier shows that the grounding line retreated up to 13 km between 1996 and 2009, giving an average rate of 1 km/yr. Offshore the ice shelf is grounded on the eastern peak, with ice elevation up to 33 m higher than equilibrium freeboard. In 2009, no evidence of grounding is seen over the western peak, the site of a former ice rumple [*Rignot*, 2001].

[19] The 2009 grounding line estimate is sensitive to uncertainty from the surface elevation and sea level at the time of measuring, the measured ice thickness and the density of the full ice column at the grounding line. Employing the densities of *Rignot et al.* [2004], a 1 m underestimate in surface elevation has approximately the same effect as an 8 m overestimate in ice thickness or a 0.001 g/cm^3 underestimate of density (assuming a typical ice thickness of 1000 m at the grounding line). Typical errors are 1.1 m for ice surface, combining laser error of 10 cm and sea surface uncertainty of 1 m [e.g., *Padman et al.*, 2002; *Andersen and Knudsen*, 2009], and 30 m ice thickness error from radar. The density of the ice column is affected by the thickness and density of the firn layer. Firn correction estimates of *Van den Broeke et al.* [2008] imply a density reduction of 1.6–2.2% over the averaged ice column, which is ~1000 m thick at the grounding line. This firn correction is partially accommodated by the assumed density of 0.9 g/cm^3, but densities as low as 0.895 g/cm^3 are considered in the error envelope.

[20] The influence of these errors on grounding line position depends on the slope of the ice surface and the bed. The width of the grounding line error envelope varies along the grounding line from 200–8000 m (Figure 3d).

[21] Even in the most conservative grounding line predictions, a region of ice within the bathymetric trough meets the conditions for hydrostatic equilibrium. A connection between this region and the main grounding line is possible within the error envelope. This analysis clearly shows that the ice above the trough is at or close to flotation, and that the path of future grounding line retreat will be guided by the bathymetric trough. The grounding line estimated here is the line of first hydrostatic equilibrium, which typically lies seaward of the InSAR derived grounding line [*Rignot et al.*, 2011]. All solutions therefore imply some retreat in the position of the grounding line across the grounding line trough with respect to the 1996 InSAR observations.

4. Discussion

[22] The present negative mass balance of Thwaites Glacier requires an increase in ice sheet velocities that shifted the system out of equilibrium before the satellite observations of the 1990s [*Rignot et al.*, 2002]. The prominent ridge in front of Thwaites Glacier presents two possible triggers for the change in mass balance, the ungrounding of the ice sheet from the ridge and the unpinning of an ice shelf from the ridge. The possible timing of these triggers is considered here in order to assess the likely significance of the offshore ridge.

[23] Retreat of the main grounding line across the inward sloping bed between the offshore ridge and the present topographic ridge is likely to have been rapid [e.g., *Hughes*, 1981]. Observed retreat rates for Thwaites Glacier of 0.35 km/yr [*Rignot*, 2001] to 1 km/yr (this study) are much faster than average rates established from geological evidence elsewhere in the Amundsen Embayment (0.008–0.4 km/a [*Smith et al.*, 2011]). At the present rapid rate, grounding line retreat across the 40 km between the offshore ridge and 2009 grounding line would have taken between 40 and 115 years. At slower rates it would have taken up to 5000 years. The grounding line at Thwaites Glacier has been relatively stable on its present topographic ridge since at least 1972, and probably since Thwaites Glacier was first sighted by the 1947 aerial survey Operation Highjump (from coastlines of *Ferrigno et al.* [1993]). The ungrounding of Thwaites Glacier from the offshore ridge likely occurred prior to the 20th century and could have occurred considerably earlier.

[24] A more recent influence on the equilibrium of Thwaites Glacier will have come from unpinning of its ice shelf from the offshore ridge. Present-day pinning of the eastern ice shelf provides back stress, diverts ice flow and contributes to much slower flow rates than seen in the ice tongue (Figures 1 and 3b, with data from *Rignot et al.* [2008]). Grounding of the floating tongue over the western peak of the ridge was identified as an ice rumple in satellite data from 1996 [*Rignot*, 2001] but new hydrostatic equilibrium calculations suggest that it was at most ephemerally grounded in 2009. The main body of the offshore ridge is on average 300 m below the base of present-day ice, and

thinning rates of the floating ice around Thwaites Glacier during the 1990s range from 2.04 ± 0.57 m/a [*Zwally et al.*, 2005] to 5.5 m/a [*Shepherd et al.*, 2004]. At these rates, floating ice could have been grounded across the offshore ridge between 55 and 150 years ago. Unpinning of the ice shelf in front of Thwaites Glacier from the offshore ridge may have contributed to the observed mass imbalance of the glacier.

[25] If the reported thinning rates apply to the eastern ice shelf, unpinning from the offshore ridge will be completed within two decades. This final unpinning would leave the eastern ice shelf unconstrained, and alter the flow along a 45 km stretch of coast. Changes in flow in this area have already been observed, with a widening of the fast flow area between 1992 to 1994 and cracks developing near the grounding line by 2005 [*Rignot*, 2006].

[26] Recent retreat of the main grounding line has been focused on the bight above the 1200 m deep grounding line trough identified here. This trough is part of the lowest topographic path from the present-day grounding line to the Byrd Subglacial Basin. The interaction between ice and ocean water in this cavity will likely play a key role in the future retreat of Thwaites Glacier grounding line.

5. Conclusion

[27] The presence of a prominent offshore ridge in front of the grounding line is a key part of the recent ungrounding history of Thwaites Glacier. The new bathymetric model presented here, from airborne gravity surveys, reveals an undulating offshore ridge that acts as a hindrance to floating ice and an obstacle for seawater circulation, and will have provided a stable position for Thwaites Glacier grounding line in the past. Ungrounding from the western part of the ridge likely contributed to acceleration in the glacier within the last 55–150 years. Ungrounding from the eastern peak in the coming decades may cause an acceleration across a wide (45 km) segment of grounding line. While the fast moving zone of Thwaites Glacier is likely to widen through this process, grounding line retreat is also expected to focus on the trough at the present-day grounding line, which could ultimately lead into the Byrd Subglacial Basin. These details of ungrounding highlight the vulnerability of Thwaites Glacier grounding line to gaps in the basement ridges that slow its retreat across its reverse bed slope. Three dimensional models of grounding line retreat are required to understand this grounding line behavior and these models must be informed by high resolution bathymetric models.

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