Seabed corrugations beneath an Antarctic ice shelf revealed by autonomous underwater vehicle survey: Origin and implications for the history of Pine Island Glacier

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[1] Ice shelves are critical features in the debate about West Antarctic ice sheet change and sea level rise, both because they limit ice discharge and because they are sensitive to change in the surrounding ocean. The Pine Island Glacier ice shelf has been thinning rapidly since at least the early 1990s, which has caused its trunk to accelerate and retreat. Although the ice shelf front has remained stable for the past six decades, past periods of ice shelf collapse have been inferred from relict seabed "corrugations" (corrugated ridges), preserved 340 km from the glacier in Pine Island Trough. Here we present high-resolution bathymetry gathered by an autonomous underwater vehicle operating beneath an Antarctic ice shelf, which provides evidence of long-term change in Pine Island Glacier. Corrugations and ploughmarks on a sub-ice shelf ridge that was a former grounding line closely resemble those observed offshore, interpreted previously as the result of iceberg grounding. The same interpretation here would indicate a significantly reduced ice shelf extent within the last 11 kyr, implying Holocene glacier retreat beyond present limits, or a past tidewater glacier regime different from today. The alternative, that corrugations were not formed in open water, would question ice shelf collapse events interpreted from the geological record, revealing detail of another bed-shaping process occurring at glacier margins. We assess hypotheses for corrugation formation and suggest periodic grounding of ice shelf keels during glacier unpinning as a viable origin. This interpretation requires neither loss of the ice shelf nor glacier retreat and is consistent with a "stable" grounding-line configuration throughout the Holocene.

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1. Introduction

[2] Environments beneath ice shelves are among the least explored on Earth's surface [*Nicholls et al.*, 2006]. The landscapes flooring the cavities of permanent, floating ice tongues are poorly understood as a result, but their geometry and sediments may provide important constraints on past, recent, or even ongoing ice shelf and glacier change [*Domack et al.*, 2005]. The same landscapes may also offer up important information on glacial bedforming mechanisms, constituting geomorphologically fresh sea-floors, likely exposed from beneath glacier ice only recently, and largely protected from open-marine influences.

[3] Of the various bedforms that record glacier ice-substrate interactions [e.g., *Clark*, 1993; *Greenwood and Clark*, 2008; *Jakobsson et al.*, 2008; *Larter et al.*, 2009; *Ottesen and Dowdeswell*, 2006; and *Stokes and Clark*, 2001], one type of fine-scale regularly spaced corrugated ridge (so-called "corrugations") has been reported with increasing frequency from formerly glaciated seabeds in the Antarctic [*Jakobsson et al.*, 2012; *Jakobsson et al.*, 2011; *Lien et al.*, 1989] and the Arctic [*Bjarnadóttir*, 2012]. In each of the few examples of corrugations documented to date, the features were concluded to have formed by the grounding of iceberg keels, and phases of past ice shelf collapse have recently been inferred by their presence [*Jakobsson et al.*, 2011]. However, while several models for

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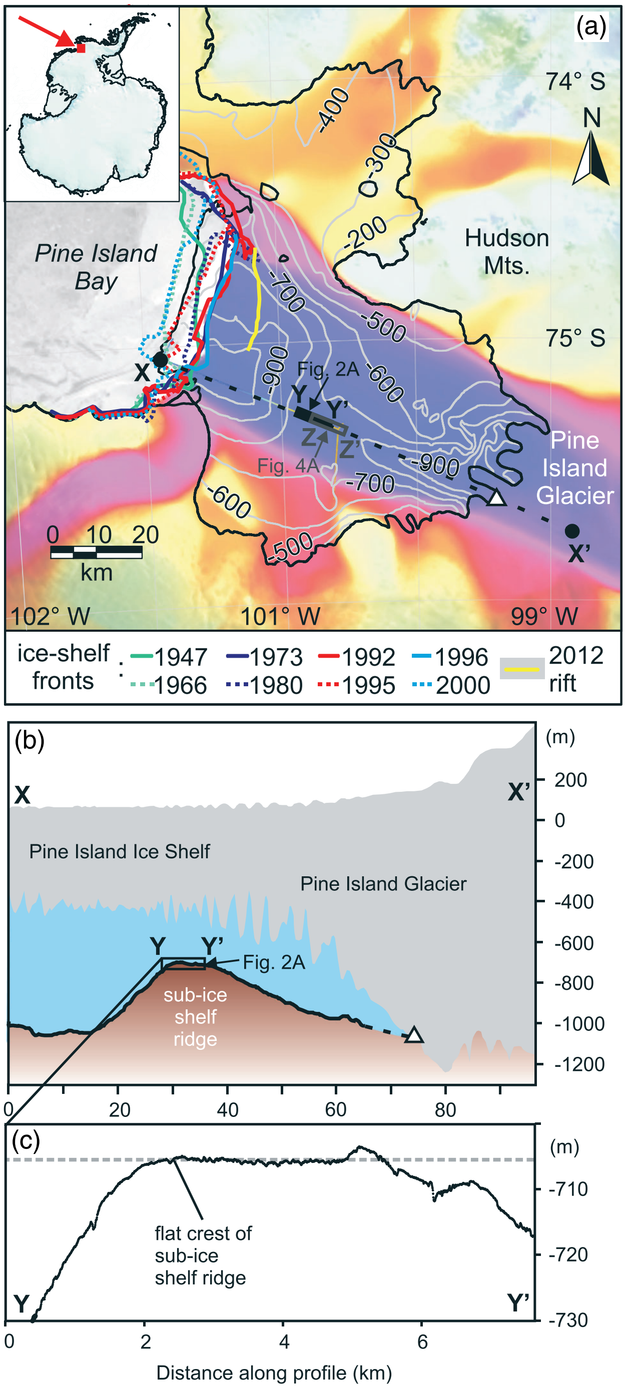

Figure 1. Pine Island Glacier study location and topographic profiles. (a) Pine Island Ice Shelf showing sub-ice shelf bathymetry (gray contours), positions of former ice shelf fronts (colored by year), InSAR velocity magnitude from ERS-1/2 data [*Rignot*, 2006] (hot colors illustrating faster ice flow), grounding/coast lines (thick black line), and location of profiles X-X′ and Y-Y′ shown in thick black and dashed lines. Black box is the location of Figure 2a, gray box shows location of Figure 4a (Z-Z′). (b) Profiles of ice base, ice surface (both measured in the 2004/2005 austral summer [*Bindschadler et al.*, 2011]), and bathymetry from Autosub mission 431 (colocated with mission 434). White triangle is position of grounding line. (c) Detailed bathymetric profile from the sub-ice–shelf ridge crest.

the origin of corrugations have been explored and, of these, a mechanism of periodic iceberg grounding within a tidally influenced ice mélange favored [*Jakobsson et al.*, 2011; *Lien et al.*, 1989], their iceberg genesis model remains controversial and untested.

[4] Here we report the occurrence of similar corrugated bedforms beneath a major Antarctic ice shelf, the floating tongue of Pine Island Glacier (Figure 1), from new acoustic bathymetry acquired by an autonomous underwater vehicle. Using data from this setting, we critically assess the origin of corrugations and examine, independently, mechanisms for their formation. Because corrugations have been suggested as diagnostic of ice shelf retreat and iceberg ploughing, their true genesis is important for the correct interpretation of ice shelf presence and absence in geological records, as well as understanding recent ice stream/ice shelf behavior in modern glacial environments.

1.1. Study Area and Context

[5] Our study area, the sector of West Antarctica draining into the Amundsen Sea (Figure 1 inset), has exhibited the most rapid rates of documented change in Antarctica's ice sheets since observational records began [*Jacobs et al.*, 1996; *Pritchard et al.*, 2009; *Rignot*, 2002]. Up to 5% of all Antarctic ice discharges via the Pine Island Glacier and its neighbor, Thwaites Glacier, and their recent dramatic changes have led to an imbalance that is now a significant contribution to current sea level rise [*Rignot et al.*, 2008; *Shepherd et al.*, 2012].

[6] The geological context for contemporary changes in Pine Island Glacier has recently been interpreted in studies of marine sediments offshore [*Hillenbrand et al.*, 2013; *Kirshner et al.*, 2012]. These show a stepwise deglaciation from the Last Glacial Maximum, with the ice margin reaching a position close to modern in inner Pine Island Bay as early as ~11,000 years ago [*Hillenbrand et al.*, 2013] and certainly no later than ~7000 years ago [*Kirshner et al.*, 2012]. The subsequent Holocene history of Pine Island Glacier is, however, not well constrained. Recent observations show that its ice shelf has thinned significantly since the early 1970s, while the glacier has undergone substantial grounding line retreat (on the order of 1 km a^{-1}) [*Rignot*, 1998]. Prior to 1973, the glacier was partially pinned on a prominent sub-ice shelf ridge and has retreated progressively inland since [*Jenkins et al.*, 2010]. In contrast, the sub-ice shelf ridge has remained permanently ice covered for at least the past 65 years, and although icebergs have regularly shed from the ice shelf front, calving has formed part of a cycle of advance and loss within a narrow "stable" (<15 km) range during this time [*MacGregor et al.*, 2012; *Rignot*, 2002] (Figure 1a). Today, the seabed beneath the ice shelf offers a rare opportunity to study the form of a freshly deglaciated grounding line that was exposed by the retreating glacier in the recent geological past. Moreover, the submerged landscape has the potential to reveal critical information on Holocene ice shelf change that is neither recorded in short-term glaciological records nor in marine geological archives.

[7] Acquiring geological information that might provide a long-term context of twentieth century retreat in Pine Island Glacier ice shelf was a key motivation for missions of the autonomous underwater vehicle (AUV) *Autosub3* that recorded water column properties, ice shelf bottom, and seafloor observations in the sub-ice shelf cavity in January 2009. The

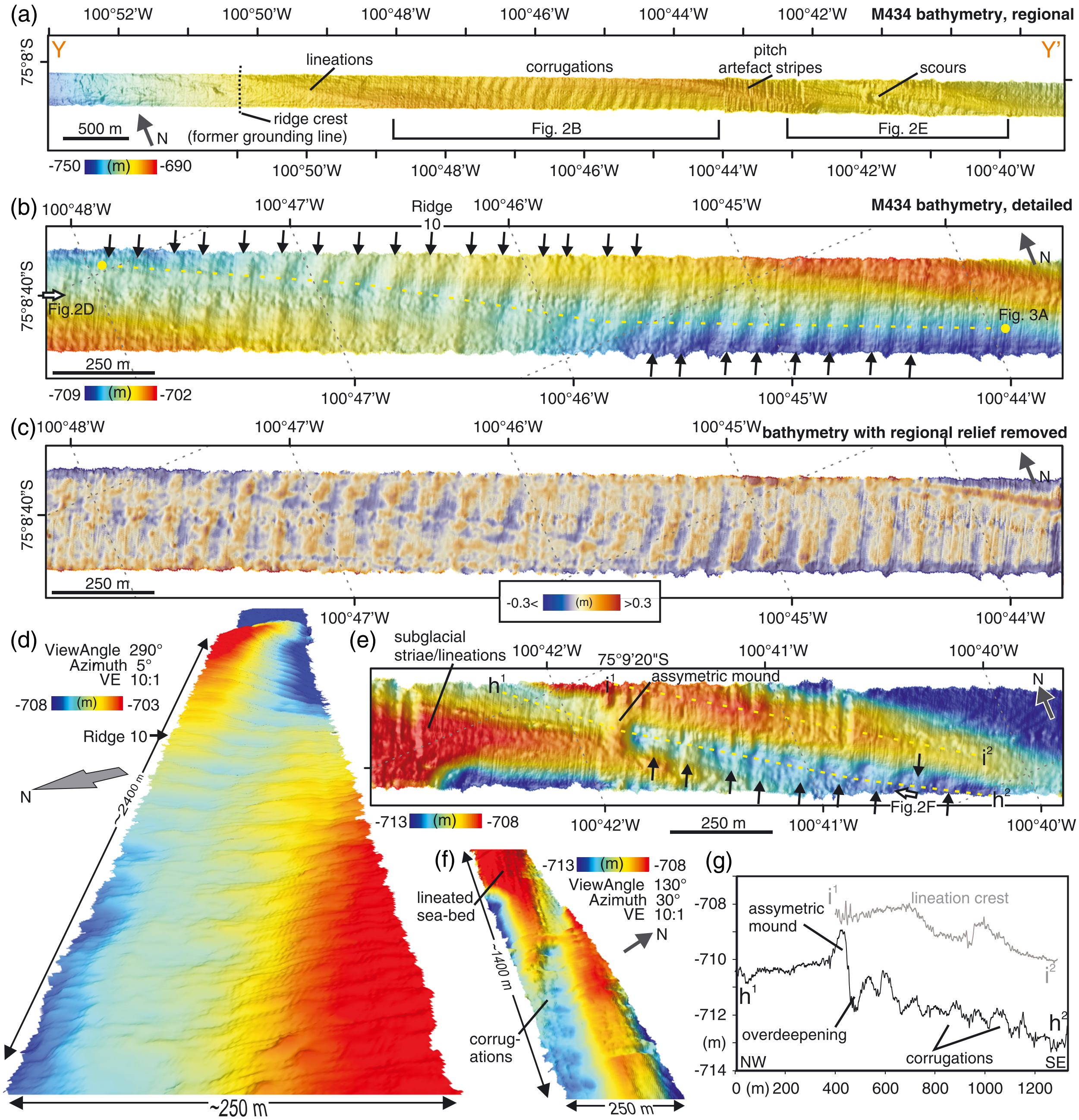

Figure 2. AUV swath bathymetry results from the ridge-crest front. (a) 2 m swath bathymetry grid from mission 434. Cross-track stripes in the bathymetry are areas of instrument artifact. Location shown as black box in Figure 1a and labeled Y-Y′. (b) Detailed bathymetry from the main set of corrugations, arrowed. (c) Residual relief separated bathymetry showing bedform component of the terrain after removal of regional relief. (d) Detailed 3-D bathymetry from the main set of corrugations, looking "up-flow" from the white arrow located in Figure 2b. Ridge number 10 marked for reference. (e) and (f) Detailed bathymetry of the ploughmarks. (g) Topographic profiles through the axis of scour and adjacent lineation.

oceanographic [*Jenkins et al.*, 2010] and ice shelf bottom topography data [*Vaughan et al.*, 2012] have been discussed elsewhere, but here we present detailed, high-resolution imagery of the seabed acquired during these missions.

2. Survey and Methods

[8] *Autosub3* was deployed from the research icebreaker *Nathaniel B Palmer* on cruise NBP09-01 to Pine Island Bay. The vehicle operated between launch and recovery without external guidance, collecting data along a preprogrammed track while navigating by dead reckoning. The AUV was equipped with a Kongsberg EM2000 multibeam echosounder, which was configured to map the sub-ice shelf topography on four out of six missions and reconfigured to map the seabed from a height of ~100 m above seafloor on its last two missions. Here we focus on one particular mission (M434) that collected multibeam swath bathymetry data up and over

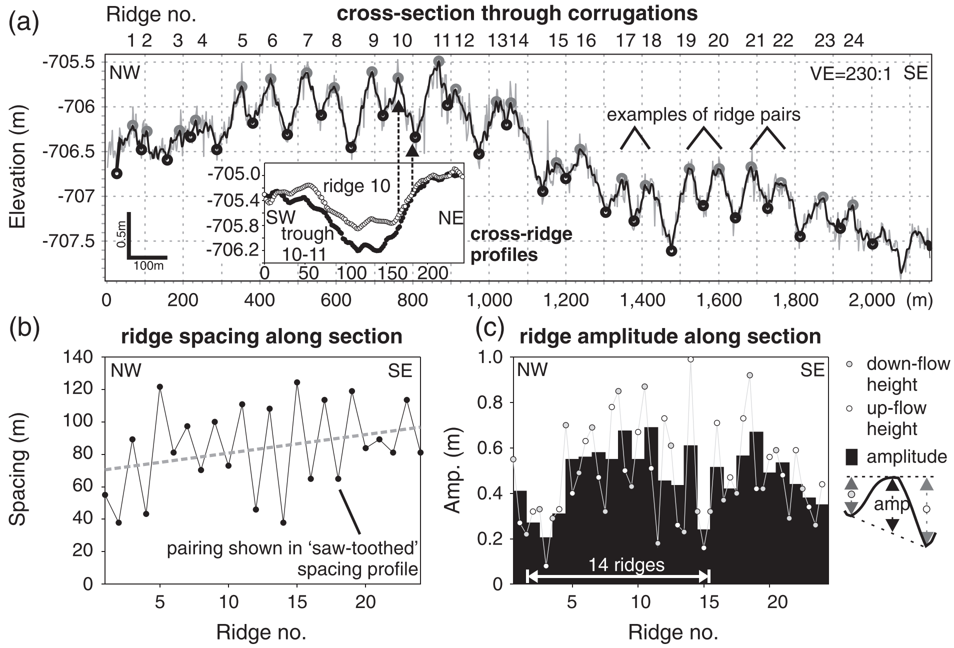

Figure 3. Cross sections and analysis of corrugations. (a) Along-track profile through corrugations shown in Figure 2b. Light gray shows bathymetry from the 2 m gridded data set, black line is the same data with a 3×3 grid-cell low-pass filter applied. Circles indicate picked ridges and troughs, while inset shows orthogonal cross-track profiles along a ridge crest and adjacent trough (marked in Figure 2d). (b) Corrugation spacing data, measured peak to peak. (c) Measured heights (circles; from lee/stoss sides, respectively) and amplitudes (black bars; an average of height data) of corrugations.

the continuous ridge that lies midway between the ice front and the grounding line (Figures 1a and 1b). Data were obtained on two overlapping lines, surveying ~30 km of seafloor across the ridge's crest and backslope (Figures 1a and 1c). Navigational uncertainty on the swath tracks accumulated at ~1 m in every thousand. Vertical error is on the order of a few centimeters. The bathymetry data were processed and gridded using a weighted near-neighbor algorithm. Grids with 2 m cell sizes were used for geomorphic analysis. Analyses of the seafloor grids included multidirectional relief shading to reveal broad morphological features (e.g., Figure 2a), detrending the bathymetry using a median filter to remove regional relief and accentuate subtle morphologies (e.g., Figure 2c; in this case, using a 68 m kernel window, following the residual relief separation method of *Hillier and Smith* [2008]), and extraction of feature geometries from seafloor profiles (e.g., Figure 3).

3. Seabed Observations From Mission M434

[9] The M434 data show glacial lineations prevalent on the ridge top (Figure 2a). Our data partially image the ridge crests of two lineations and two intervening grooves (Figure 2b). Lineations are at least 1 km long, but could be significantly longer. They are >150 m wide, ~2–6 m high, and elongated in the direction of modern ice flow. Lineation metrics, sinusoidal cross-profile shape, and streamlined and parallel form are all typical of mega-scale glacial lineations mapped on the beds of modern and past ice streams [*Clark*, 1993; *Stokes and Clark*, 1999, 2001]. Thus, lineations may be subglacial bedforms formed during the most recent episode of glacier grounding, which probably also served to plane off the distinctive ridge crest, which is nearly flat over a distance of ~3 km (Figure 1c). Alternatively, ridge grooves may have formed by interaction with a partially grounded ice shelf and therefore do not represent true sub-ice stream lineations. Either way, the lineations appear indicative of glacier grounding, and their extent to the ridge front suggests that, as observed for the northern ridge flank [*Jenkins et al.*, 2010], the grounding line was likely pinned on the southern part of the ridge in the recent past. Recent radiocarbon age dating of marine sediments recovered in cores ~100 km from the modern grounding line suggests that the retreat of Pine Island Glacier into the inner part of Pine Island Bay had already occurred by ~11–10 kyr before present *Hillenbrand et al.* [2013], and, thus, that the newly mapped lineations probably reflect grounding since the start of the Holocene.

[10] A population of at least 24 parallel ridges, transverse to modern ice flow and orthogonal to the lineations, overprint the seabed lineations in the western part of the data set, within a groove between lineation ridges (Figures 2a–2d and 3a; numbered individually from 1 to 24 in both figures). These pristine corrugations exhibit a remarkably regular spacing (Figure 2c), averaging 84 m crest to crest, and slightly decrease in spacing downstream (Figure 3b). Crest-trough heights and mean corrugation amplitudes are extraordinarily low, ranging 0.1–1.0 m and 0.2–0.7 m, respectively (Figure 3c). The spacings and heights of corrugations also reveal two rhythmic trends along flow: one a prominent pairing and the other a potential longer period cyclicity (two apparent cycles spanning 11 and 13 ridges, respectively, out of 24 observed), both observable in cross profiles (Figures 3a and 3c). In a downflow direction, the

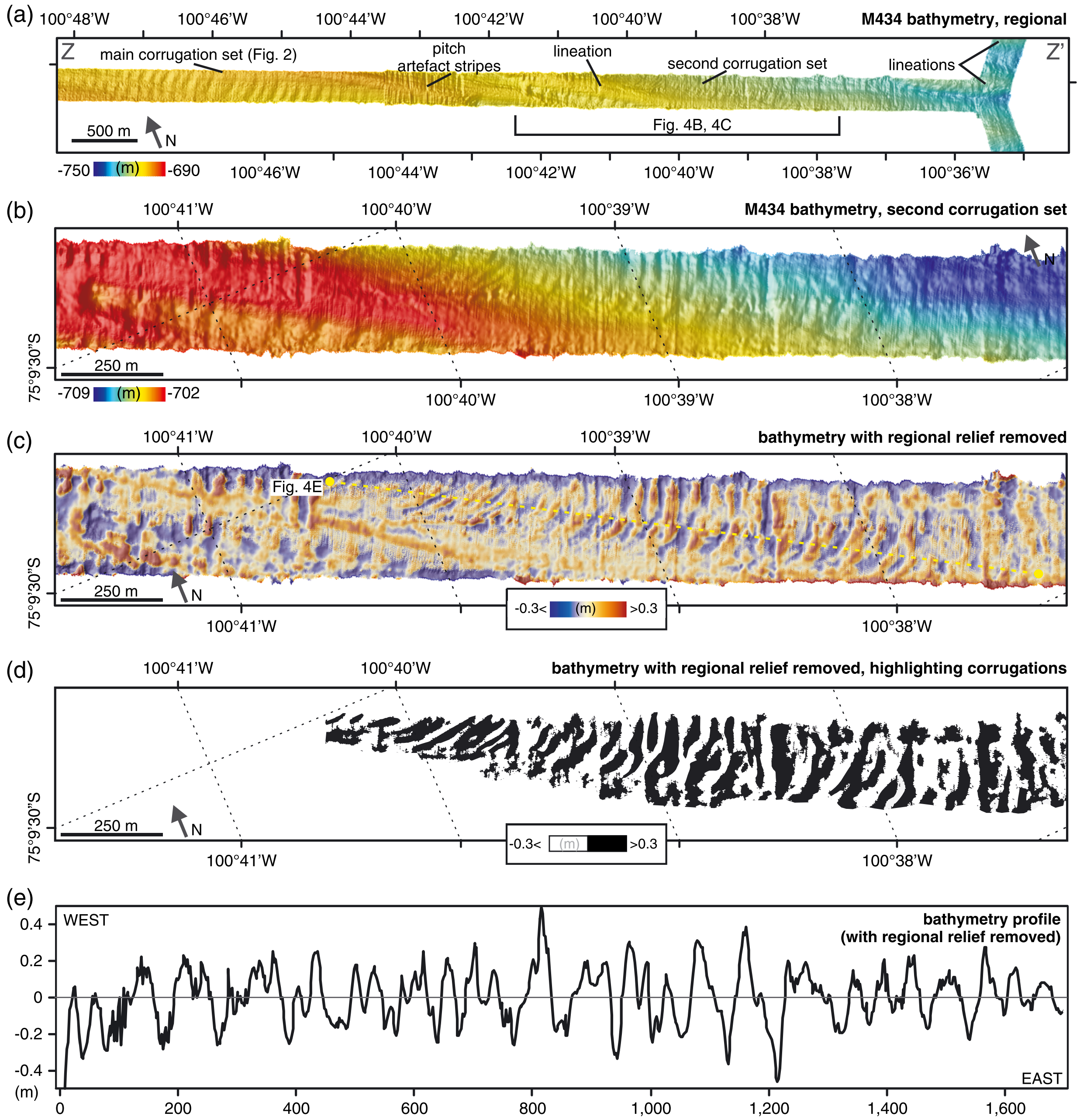

Figure 4. AUV swath bathymetry results from the ridge-crest backslope. (a) 2 m swath bathymetry grid from mission 434 in the southeastern part of the dataset. Cross-track stripes in the bathymetry are areas of instrument artifact. Location shown as gray box in Figure 1a and labeled Z-Z′. (b) Detailed bathymetry from the second set of corrugations. (c) Residual relief separated bathymetry showing bedform component of the terrain after removal of regional relief. (d) Visualisation of corrugations from the detrended bathymetry in Figure 4c. (e) Topographic profile through the detrended grid in Figure 4c illustrating amplitude and spacing of corrugated topography.

corrugations show a gradual change in morphological expression from a straight/concave to convex planform geometry (Figures 2b and 2c). The detrended bathymetry also shows that corrugations are more pronounced within the groove between lineations, but are nevertheless continuous across the swath, thinning across the sides and crests of adjacent lineation ridges (Figure 2c).

[11] Upstream of the corrugations, the seabed expression comprises two prominent linear “depressions,” >500 m and 900 m long, 2–7 m deep and narrower than the grooves between the westernmost lineations, at 80–~150 m wide (Figures 2e–2g). These depressions also appear to be cut deeper than the surrounding seafloor. The two features terminate abruptly at their downstream ends, with the northern feature exhibiting a prominent ridge at its terminus (Figures 2e–2g).

[12] Beyond the depressions, the bathymetry data partially image a second groove between lineations (the start of the groove is visible in the far right-hand side of the image in

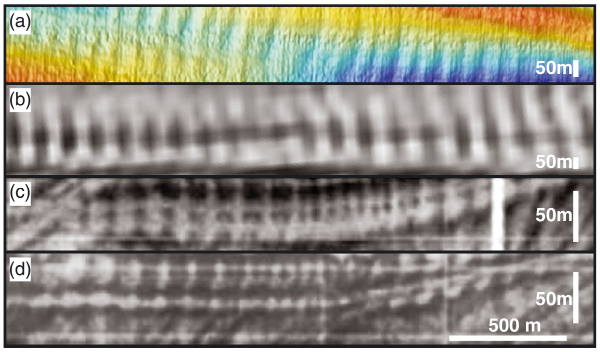

Figure 5. Comparison of Antarctic corrugations. (a) From this study. (b) Pine Island Trough (EM122 multibeam swath bathymetry, from Cruise OS0910 of the RV *Oden*). (c and d) The JOIDES basin, Ross Sea (side scan sonar records, Cruise NBP9801 of the RV *Nathaniel B Palmer* [*Anderson*, 1999]).

Figure 2a). Seabed features on the bathymetry data within the groove are indistinct (Figure 4b), but the detrended bathymetry grid reveals a second set of 32 or more further corrugations (Figure 4c). Like the first set (Figure 2b), the second set are parallel, transverse to flow, pronounced within the groove, of a similar amplitude (12–82 cm, modal amplitude of 34 cm) and spacing (22–82 m with a modal spacing of 53 m), and appear evenly spaced downstream. Mapped out, the corrugations curve to the east, changing their bend gradually downflow (Figure 4d), and exhibit occasional pairing in the ridges, although no longer period modulation is observable as inferred for the main set of features (Figure 4e). Unlike the first corrugation set, the corrugations occur on a very gentle upslope (+7 m relief over 1700 m) and are less continuous across the swath. They also frequently appear anastomosing and broken up (discontinuous) (Figures 4c and 4d). It is not clear whether these disjoints are real, a function of the detrending process, or due to the small sizes of the features that are approaching the limit of resolution. Either way, the subtlety in expression of the second set of corrugations leaves us cautious about inferring too much from their metrics. Inland of the second corrugation set, the seabed remains lineated along the ridge backslope (Figure 4a [*Jenkins et al.*, 2010]) and falls away to the East beneath a 400 m-thick ocean cavity that has opened as the glacier has thinned (Figure 1b).

4. Interpretations and Discussion

4.1. Iceberg Theory of Corrugation Formation

[13] Recent mapping in the relict trough of the ancestral Pine Island Glacier, oceanward of the modern glacier system, documented sets of regular 0.2–3.4 m high ridges on the seafloor from which phases of past ice shelf collapse were inferred [*Jakobsson et al.*, 2011]. All the significant features of our corrugations (wavelengths, heights, regularity, gradual changes in planform shapes, spatial arrangement, and amplitude variations) suggest that they are entirely similar and were formed by a comparable (if not identical) process to those in Pine Island Trough [*Jakobsson et al.*, 2011] (Figure 5). Those corrugations were interpreted by Jakobsson et al. as evidence of open-water conditions, during which icebergs came into contact with the seabed. Their proposed mechanism for formation involved the daily creation of ridges by tidal squeezing of sediment at the trailing margin of a seaward-traveling iceberg entrained in a mélange of ice (a weak though dense proglacial mixture of icebergs and brash ice) shed from the calving front.

[14] Comparable features referred to as "washboard patterns" have also been described in the Ross and Weddell Seas and have, similarly, been interpreted as the product of ice-keel grounding through iceberg "wobble"—explained by previous authors as small rotations of an iceberg around an equilibrium position, influenced by the tides, and forced forward by currents, winds, or direct pushing by shelf or pack ice [*Barnes and Lien*, 1988; *Jakobsson et al.*, 2011; *Lien et al.*, 1989] (supporting information Figure S1). These are distinct and irrefutably iceberg-formed features, owing to their confinement to curvilinear grooves, with adjacent iceberg-ploughed berms. The M434 corrugations have the same form as other Antarctic shelf examples, overprinting streamlined lineations on a flat or gently shoaling ice-planed surface, decreasing subtly in spacing downstream, and seemingly more pronounced in the grooves between lineations (Figure 3a inset, Figure 5, and supporting information Figure S1). The progressive change in planform shape in both sets of M434 corrugations is also reminiscent of data described by Jakobsson et al., which show kinks and bends in ridges that develop gradually from one corrugation to the next [*Jakobsson et al.*, 2012, 2011].

[15] A key feature of the corrugations in Pine Island Trough, which has been argued to indicate that they were formed by icebergs, was the presence of an apparent tidal signal in their amplitudes. In particular, a periodic amplitude modulation over 14 corrugations was observed that might indicate a fortnightly spring-neap cycle [*Jakobsson et al.*, 2011]. The two chains of corrugations in the M434 data are too short to expect a similar modulation to be verifiable quantitatively, but two prominent crests in the amplitudes profile from our main set hint at a periodicity consistent with a tidal modulation (~11–13 ridge peak frequency; Figure 3c). Thus, our data support one interpretation that the ridge sets were shaped by iceberg interactions with the seafloor, in the same manner suggested for those in Pine Island Trough.

[16] This notion appears supported, independently, by the two scours mapped on the ridge backslope which can plausibly be interpreted as iceberg ploughmarks (Figures 2e–2g). The shallowing axis of the northern linear scour also contains a set of 70–100 m regularly spaced, ~1 m high corrugations, while an asymmetric mound at the scour head resembles a typical ice-keel ploughed pressure ridge. Though partially imaged, the southern scour is clearly downward cut into seabed that is subglacially lineated and also has an overdeepened, semicircular terminus, common to iceberg ploughmarks on glaciated continental margins [*Hill et al.*, 2008]. None of these characteristics are diagnostic of streamlined subglacial bedforms, despite their linearity, and thus we argue that the scours were more likely formed through erosion by sub-ice keels (free-floating or otherwise). If this is indeed the case, then parallel streamlined lineations imaged extensively across the ridge and backslope, with the appearance of subglacial bedforms, must also have formed by ice-keel ploughing rather than subglacial processes; it seems implausible otherwise, that corrugations would form

neat ladders within the confines of subglacial grooves while leaving adjacent bedform ridges unmodified.

4.2. Alternative Hypotheses for Corrugation Formation

[17] An iceberg hypothesis, if correct, would necessarily imply a much reduced calving front on Pine Island Glacier at some point during the Holocene. Given that there is, thus far, no independent evidence in support of this scenario, we explore how robust a conclusion this would be by considering whether there are alternative mechanisms which could form corrugations. Indeed, the presence of corrugations beneath an extant ice shelf, which was until recently grounded nearby, and within features that appear indicative of grounded ice flow, may require a new theory to explain their formation. Supported by a matrix of geomorphic characteristics, we assessed a range of physical processes for corrugation formation to establish whether there are plausible alternatives to the iceberg hypothesis.

4.2.1. Sub-Ice Shelf Keel Grounding

[18] One hypothesis is that the M434 corrugations formed beneath the thicker, intact ice shelf as it floated off its bed. An ice keel protruding from the irregular ice shelf base, driven forward at a regular pace by glacial flow, grounded periodically, loading the seafloor and squeezing up sediment in a ridge behind it (notably akin in physical terms to Jakobsson et al.'s iceberg grounding mechanism; presumably, the main ridge-forming process would be a combination of sediment bull-dozing and extrusion). The fact that corrugations are most pronounced within grooves may support an ice-keel grounding interpretation and further suggest that the lineations on the sub-ice shelf ridge reflect groove-ploughing by grounded keels and not true sub-ice stream bedforms as mentioned previously. Longitudinal channels at the base of the modern ice shelf show that it is indeed keeled along the direction of ice flow [*Vaughan et al*., 2012], which would fit this hypothesis (Figure 1b).

[19] Since the daily advance inferred from modern ice shelf flow rates (approximately $7\,\mathrm{m\,d^{-1}}$ [*Bindschadler et al*., 2011]) is approximately an order of magnitude lower than the spacing of our corrugations (approximately 50–80 m), an ice shelf grounding process would not be feasible if ridges were formed daily (as has been suggested for other examples of corrugations [*Jakobsson et al*., 2011]). However, our spacing measurements could be reconciled if one ridge formed at the peak of every spring-neap cycle (fortnightly), rather than daily. In this case, the lower frequency modulation in amplitudes (at~11–13 ridges) would be consistent with a seasonal or annual cycle, while the pairing of ridges may reflect ice shelf response to another tidal effect. Vertical motion of a floating ice shelf is generally representative of the response of the ocean height to tide [*Gudmundsson*, 2011], and displacements of the magnitude associated with corrugation heights (i.e., ±1 m) are expected on Pine Island Glacier ice shelf [*Padman et al*., 2002]. Moreover, we would predict episodes of ice shelf grounding to reflect a 14 day spring-to-neap cycle because it dominates in observed patterns of ice shelf motion [*Brunt et al*., 2010].

[20] Importantly, the tidally modulated grounding of an ice shelf keel would be able to produce the ploughmarks containing corrugations, as well as the regularity and consistent forward motion implied by geomorphic observations from the main set of corrugations, which is difficult to achieve in floating icebergs unless trapped in an ice mélange (as suggested by *Jakobsson et al*. [2011]). The downflow change in planform shape observed in both the corrugation sets may also be representative of a gradual seaward change in ice-keel shapes as they progressively melted.

[21] We propose sub-ice shelf keel grounding as a plausible alternative to iceberg grounding.

4.2.2. Subglacial Bedforming (Till-Ribbing or Water-Lain Deposition)

[22] A third hypothesis is that corrugations were created as bedforms beneath the ice sheet by a self-organizing instability caused by the interaction between ice, or subglacial water, and its sedimentary bed (i.e., as a type of ribbed moraines formed as waves in a deforming till layer, or as ripples formed by water flow over sediment, similar to current ripples formed on a beach). Whether through the flow of till or water, such a mechanism could possibly account for the different frequencies in the main set of M434 corrugations: the pairing in ridges, their possible longer wavelength cyclicity in amplitudes, in addition to their regular spacing and symmetry. In support of an ice-till hypothesis, ribbed-till bedforms produced beneath the former Northern Hemisphere ice sheets possess geometries and landform associations consistent with the M434 corrugations, our newly mapped features falling toward the lower end of size ranges quoted for ribbed moraines [*Dunlop and Clark*, 2006]. The narrow tracks, up/down-streaming curving ridges, and gradual downflow change in planform shape in both sets, as well as the broken arrangement and anastomosing of the features in our second (Figure 4d), are certainly all traits of ribbed moraines shown by field mapping [*Dunlop and Clark*, 2006] and modeling studies [*Chapwanya et al*., 2011]. The extreme consistency in the spatial pattern of corrugations is also a characteristic of naturally arising phenomena, such as in drumlins, which has led to the idea that many types of subglacial bedform are created by unstable behavior in the subglacial system [*Clark*, 2010]. Furthermore, although typically limited to "core areas of glaciation" [*Dunlop and Clark*, 2006], we would expect to find ribbed bedforms in areas of former grounding where the ice and bed were strongly coupled, such as upon a bedrock or sediment ridge.

[23] An argument against the ribbed bedform hypothesis is that in order to preserve ribbed bedforms, the marginal part of the glacier would need to have ungrounded almost instantaneously during the deglaciation of the sub-ice shelf ridge. This scenario appears unlikely. In addition, transverse ribbed bedforms are not typically associated with ice-marginal glacial land systems, even where ice sheets are known to have been pinned for significant periods in the past (e.g., such as upon Grounding Zone Wedges), although there are a few noteworthy exceptions [*Stokes et al*., 2006; *Stokes et al*., 2008]. However, even in these rare cases, corrugated ridges also appear to overprint the lineated surface and modify the lineation ridges themselves, rather than nest purely within lineation grooves.

[24] A variant of this instability interpretation which might overcome necessitating a rapid "lift off" is if corrugations formed in subglacial streams while the glacier was grounded. In the same way that sediment wave fields form in tidal inlets, turbulent meltwater flow in channelized cavities that emerged at the ice sheet terminus could have organized channel-bed sediments into corrugations. This would require that

the glacier was close to unpinning at its terminus, with ice grounded on the crests of streamlined subglacial bedforms but ungrounded in the intervening grooves when corrugations were formed. Open "Röthlisberger" channels between ridges [*Röthlisberger*, 1972], ejecting fresh, buoyant subglacial meltwater at the grounding line, would entrain warmer seawater which could further excavate the channel walls, promoting basal melt and glacier thinning [*Jenkins*, 2011]. This configuration would also lead to corrugations being more pronounced, and subsequently well preserved, within grooves between lineations as the glacier retreated and lifted off its bed; a preservation that seems unlikely if corrugations were formed as ice-contact forms (e.g., ribbed-till bedforms, but also as basal crevasses).

[25] Theory predicts the flow of a thin unstable water layer in the rills between elongate ice stream lineations as hypothesized here [*Fowler*, 2010]. A meltwater origin is also consistent with corrugation dimensions, because low-amplitude waves formed by bottom currents, which can be seen as analogous to our corrugations, are produced at low to average flow velocities (0.1–0.75 ms^{-1}; [*Stow et al*., 2009]) within the range estimated for meltwater discharge in tunnels during drainage events beneath the modern ice sheet (0.1–2.1 ms^{-1}; [*Wingham et al*., 2006]). A process akin to subglacial stream flow (e.g., water flow in bottom currents) might also account for the formation of similar corrugations within arcuate open-water scours that are clearly iceberg formed (proposed previously, for example, by [*Hill et al*., 2008]) but which are not readily explainable by sub-ice shelf or subglacial mechanisms.

[26] An important piece of evidence to test such a meltwater theory would be the internal composition of the ridges. Unfortunately, we have no sediment core data from under the ice shelf, but those collected in fields of relict corrugations from Pine Island Trough recovered glacial diamicts and sandy glacimarine clays that are not glaciofluvial in nature (i.e., poorly sorted, lacking gravels [*Jakobsson et al*., 2011]). Thus, while the geometry of corrugations does not exclude a meltwater genesis, and there is evidence for sediment-laden meltwater emerging at the glacier grounding line today [*Jenkins et al*., 2010], the available sedimentological data appear to be inconsistent with meltwater deposition.

4.2.3. Grounding Line Deposition

[27] Another obvious consideration for the creation of corrugations is their production as moraines at the grounding line, with ridges formed of sediment carried by the glacier and deposited at the grounding line, by a combination of sediment advection, ice-push, thrust, and/or squeezing, during periodic halts or minor readvances. However, a process that would provide the regularity, symmetry, or cyclicity to explain a grounding line interpretation is difficult to envisage at present, particularly because the spacing between individual corrugations is too great if tidal modulation was daily; past retreat rates would have to have been on the order of 25–37 km/yr, an order of magnitude higher than modern "fast" retreat. If a 14 day spring-neap tidal influence is accepted instead, the physical process to explain the generation of grounding line moraines, which retain a ~14 day periodicity within their amplitudes, is still unclear. Tidal flexure at, and inland of, the grounding line is predicted, but with exceptionally low vertical displacements: on the order of 1 cm [*Walker et al*., 2013], which would not be consistent with the formation of corrugations up to ~1 m in amplitude. Likewise, it is not clear why corrugations would be produced at such a consistent and regular spacing if formed marginally or why they would exhibit a distinct gradual change in their planform shape along flow. Annual or seasonal moraine ridges are common in deglaciated submarine and terrestrial landscapes [*Matthews et al*., 1995; *Ottesen and Dowdeswell*, 2006; *Sharp*, 1984; *Shaw et al*., 2009], formed during minor grounding line readvances, but there is no indication in the morphological data, in terms of size, cross-profile, or plan shape, that our corrugations represent either: there are few examples of such extreme regularity in moraines, and where chains of moraines are documented, they are often asymmetric in profile [*Winkelmann et al*., 2010], unlike the M434 corrugations. In addition, we argue that the corrugations mapped within the two scourmarks on the eastern flank of the sub-ice shelf ridge cannot be attributed to deposition at a retreating grounding line, because they are found within isolated incisions, cut downward into the seabed. Thus, we do not favor a grounding line origin of corrugations.

4.2.4. Crevasse-Squeeze (-Fill) Ridges

[28] As with grounding line moraines, we also rule out an origin of corrugations as crevasse-squeeze ridges: open basal crevasses that have become infilled with water-saturated sediment intruded from the glacier base due to changes in effective pressure at the bed or through overburden [*Sharp*, 1985]. Several lines of evidence would accommodate the interpretation: crevasse-squeeze ridges are normally composed of water-laden diamicton, readily available in an ice stream grounding zone to which soft, saturated till is advected; and ridges are typically associated with other ice-flow indicators (e.g., lineations or fluted surfaces) [*Rea and Evans*, 2011].

[29] However, while surface crevasses in ice streams possess a quasi-periodicity (and thus regular spacing might be expected), most examples of geomorphic products of basal crevasses that have been sediment filled are irregularly shaped and discontinuous in planform and do not require a geometric relation to the position of the ice front [*Sharp*, 1985]; in fact, they are often observed as rhombohedral forms [*Bjarnadóttir*, 2012; *Ottesen and Dowdeswell*, 2006] and are discordant with other ice-marginal moraines [*Ottesen et al*., 2008]. In contrast, the M434 corrugations are regular, often continuous, and lie conformable to the modern ice shelf front.

[30] In addition, the cross-profile shape of crevasse ridges generally reveals sharp crests and steeper flanks [*Ottesen and Dowdeswell*, 2006], whereas the corrugations we have mapped are extremely low amplitude and broadly spaced, forming a gently rolling surface. There is no reason why crevasse-fill ridges should also nest within glacial lineations, as we observe.

[31] Morphometry aside, as suggested in previous work [*Jakobsson et al*., 2011], it is highly unlikely that a field of crevasse-squeeze ridges could be preserved below wet-based grounded glacier ice: the forward motion of the ice stream would obliterate the basal record of crevassing, unless thinning and lift off were almost instantaneous, which is unlikely. The only other practicable method for preserving crevasse-fill ridges would be through ice stagnation: the best preserved crevasse-squeeze ridges in Northern Hemisphere deglaciated forelands record emergent features at the

terminus subsequent to glacier surge and during a phase of quiescence/stagnation (which must explain their survival through the following glacial retreat) [*Ottesen et al*., 2008]. However, we consider it unlikely that in situ stagnation would occur in the terminus of a fast-flowing marine-terminating ice stream such as Pine Island Glacier, even if the grounding line was stable on its sub-ice shelf ridge, and to our knowledge there is no corroborating evidence for past or recent surge-like behavior in the Pine Island Glacier system. Thus, corrugations within grooved sub-ice shelf bedforms probably did not form by this process. Even if a regular imprint of crevasses could be formed, we would also expect them, in this case, to have an along-flow component to their form, because the ice-base morphology below the Pine Island Glacier ice shelf today is predominantly longitudinal [*Vaughan et al*., 2012]. This is not consistent with our observations of corrugations, formed perpendicular to flow.

4.2.5. Sediment Waves by Ocean Currents

[32] We last consider corrugations as sediment waves formed by ocean currents. The ubiquity and range of types of sediment wave in nature means a form analogy for our corrugations can be found in several places [*Stow et al*., 2009]. The prominence of corrugations within grooves and changes in their planform shape are plausible for current forms, as is a tidal modulation (tidal currents might be expected near a grounding line). With regard to composition, the characterization of sediments in sub-ice shelf environments is generally poorly known, but the availability of coarse well-sorted sediments is thought to be low, which does not favor the formation of sandy sediment waves. However, the sands and gravels deposited within meltwater channels, as discussed previously, might provide suitable substrates for later current ripple production, and, again, there is evidence that sediment-rich meltwater emerges at the glacier margin today [*Jenkins et al*., 2010]. Furthermore, in one previous study, similar corrugations mapped within relict iceberg ploughmarks were interpreted as current-formed waves, based on bottom-camera observations indicating sandy surficial sediments [*Hill et al*., 2008]. However, as with the subglacial meltwater hypothesis, there is currently no direct geological evidence to support or conclusively reject a current-forming mechanism. A 4-D time-lapse survey, with repeat mapping of the corrugation chains, would serve as a test of an active sediment-wave hypothesis in future work beneath the ice shelf [e.g., *Van Landeghem et al*., 2012].

4.3. Summary: Origin of Corrugations

[33] In summary, several processes occurring in nature could have produced the M434 corrugations: some in open water and others beneath floating or grounded ice. From detailed side scan sonar images of the relict seafloor in the Weddell Sea [*Barnes and Lien*, 1988; *Lien et al*., 1989], it is clear that corrugations do occur in some areas of former iceberg scouring, and examples of corrugated bedforms surrounding and within curved ploughmarks provide strong evidence that "wobbly" icebergs, as proposed by Lien et al., do generate corrugated forms in some cases. In the Ross Sea, Antarctica, there is also evidence for well-aligned corrugation ridges extending seaward into slightly more sinuous ridges and finally into highly sinuous furrows, with corrugations, that crosscut [*Anderson*, 1999], indicating an association of corrugation ridges in this location with ice that is at or near to the point of floating.

[34] For the M434 corrugations, the formational mechanism is not clear-cut, and in the absence of physical samples or more extensive multibeam coverage below Pine Island Glacier ice shelf, there remain persuasive arguments both for and against individual mechanisms from the range that have been proposed. The key observations we have presented that determine which process is most likely are the following: (1) the discovery of corrugations in a persistent sub-ice shelf setting, (2) in association with landforms indicative of recently grounded ice, (3) extreme regularity, (4) apparent modulation indicative of tides, and (5) occurrence alongside scourmarks suggestive of incision by forward motion.

[35] Based on these observations, we propose that forward ploughing of an ice keel in the part of the glacier where it begins to float is a primary candidate for corrugation development, which occurs through sediment squeezing by the keel as the ice flexes or rises and falls with the tides. This plausibly describes a mechanism occurring in a variety of different environments: beneath the ice shelf, in the grounding zone, or indeed behind newly calved icebergs at the grounding line [cf. *Jakobsson et al*., 2011]. Crucially, however, these different environments yield different reconstructions of Pine Island Glacier's grounding- and calving-line histories.

5. Implications for Pine Island Glacier History

[36] High-resolution AUV bathymetry data presented here from beneath an intact ice shelf, in an area that we interpret as a recently deglaciated grounding line, shows sets of corrugated bedforms that have the potential to challenge our current understanding of Pine Island Glacier's history.

[37] If prevailing interpretations of corrugation formation are correct [*Jakobsson et al*., 2011], and we accept that the sub-ice shelf ridge was scoured by icebergs, the extent of Pine Island Glacier's ice shelf must have been significantly reduced in the past, with the calving front a minimum of 32 km inland of its current position, very close to the modern grounding line. Based on existing offshore chronological data as well as observations from satellite imagery, this event must have occurred prior to 1947 [*Rignot*, 2002] but within the last 7–11 kyr [*Hillenbrand et al*., 2013; *Kirshner et al*., 2012]. Direct evidence for a reduced ice shelf on Pine Island Glacier during the Holocene would imply that either (1) Pine Island Glacier existed in a different configuration as a tidewater-like glacier during the Holocene (i.e., grounded near to present position, marine calving, but without a significant floating ice tongue so that iceberg production takes place near to the grounding line, perhaps comparable to Jakobshavn Isbrae today); or (2) a calving front located inland of the sub-ice shelf ridge was also associated with a grounding line position upstream of present-day limits. Holocene variations in a large marine-terminating glacier might, indeed, be expected. Our data would thus provide the evidence documenting a period of inland retreat and, importantly, imply that the Pine Island Glacier system was resilient to that retreat and underwent punctuated readvance to its modern configuration.

[38] However, if corrugations were not iceberg formed in this case, recent interpretations of rapid ice shelf collapse during West Antarctic deglaciation are open to renewed debate. Corrugations would then provide evidence of another process occurring beneath intact glaciers or ice shelves. We do not favor ribbing in till or basal crevassing as potential mechanisms given the difficulty in preserving features. There are geological indicators from indirect sources in Pine Island Trough which suggest a subglacial meltwater mechanism is also unlikely, although, morphologically, a meltwater deposition process is plausible.

[39] The simplest and least objectionable alternative to iceberg action is the periodic grounding of sub-ice shelf keels during the final phases of glacier unpinning. Critically, the physical process underpinning this hypothesis is similar in nearly all aspects to that proposed originally by *Jakobsson et al*. [2011], and indeed to that of *Lien et al*. [1989]. It is therefore possible that separate mechanisms could lead to the formation of identical corrugation sets through the same fundamental process. We propose this as the most likely explanation for the creation of M434 corrugations, for the scourmarks containing corrugations on the ridge backslope, and as a way of reconciling a non-iceberg theory with the existence of corrugations in curvilinear scours that are clearly iceberg formed [*Anderson*, 1999; *Lien et al*., 1989]. Under this scenario, the corrugations record the last phase of ice shelf grounding on the sub-ice ridge, prior to its complete flotation, providing insight into the physical processes underpinning recent deglaciation. Furthermore, this interpretation would not require, nor provide evidence of, Holocene retreat of Pine Island Glacier's calving front beyond its present position. It would thus remain consistent with interpretations of a stable Holocene grounding line configuration [*Hillenbrand et al*., 2013] prior to the dramatic changes observed on the glacier in recent decades [*Joughin and Alley*, 2011; *Joughin et al*., 2010; *Rignot*, 1998]. An important caveat is that we cannot rule out grounding line deposition or even oceanic currents as other viable mechanisms and that all of the above hypotheses remain the focus of future testing.

[40] Taking either of the "end-member" interpretations (iceberg versus non-iceberg formed), it is important that the issue of corrugation genesis is resolved if we are to understand properly the significance of current changes in Pine Island Glacier. One of the largest calving events in observational history is currently under way on the ice shelf [*Howat and Jezek*, 2012] (Figure 1a). It is important that we establish whether such events are unique within the Holocene context, or are simply an expression of the shorter-term variability in glacier configuration. Further understanding of Pine Island Glacier's Holocene history, and of the seabed record beneath its ice shelf, is fundamental to achieving this.

6. Conclusions

[41] 1. High-resolution bathymetry data gathered by missions of an autonomous underwater vehicle, operating beneath Pine Island Glacier ice shelf, have revealed sets of corrugated ridges (corrugations) and isolated ploughmarks on a prominent sub-ice shelf ridge (a former and likely recently deglaciated grounding line), which closely resemble those observed offshore, interpreted previously as the result of iceberg grounding.

[42] 2. Several lines of evidence, including ridge morphometry and an apparent tidal modulation, indicate that the iceberg mechanism used to explain identical features elsewhere may be plausible for the newly mapped corrugations. If prevailing interpretations of corrugation formation are correct and exclusive [*Jakobsson et al*., 2011], in order for icebergs to scour the sub-ice shelf ridge, the extent of Pine Island Glacier's ice shelf must have been significantly reduced during the Holocene, with implications for the configuration and extent of the glacier itself.

[43] 3. Alternative hypotheses for corrugation formation include a range of processes operating in open water and acting beneath ice. We argue that a sub-ice shelf keel grounding model best fits the observations from our study area. This alternative hypothesis would not require past changes to the extent of Pine Island Glacier ice shelf and would instead raise a potential challenge to interpretations of paleo-ice shelf collapse from areas where corrugations have been mapped more extensively.

[44] 4. Irrespective of whether free-floating as an iceberg or part of an intact ice shelf, formation by ice keels currently stands out as the most plausible mechanism for corrugation formation.

[45] 5. Considering corrugation formation more widely, the main limitation of the data set we have presented is its size: we recognize it is not possible to fully test hypotheses for corrugation production from this dataset alone. However, corrugations are now seen in increasing numbers of records from former ice stream beds (this study included), from which a coherent picture is emerging that suggests corrugations may be an important component of landscapes formed by marine ice stream/ice shelf retreat [*Bjarnadóttir*, 2012; *Jakobsson et al*., 2012; *Jakobsson et al*., 2011]. Direct observation of corrugations forming in nature and further detailed investigation of corrugations from relict landscapes can thus improve our understanding of these enigmatic features. In doing so, they are likely to add to our knowledge of the detailed processes involved in ice sheet deglaciation, particularly those that concern glacier detachment from its bed and the potential influence of tides on glacial retreat [*Ó Cofaigh*, 2011].

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