Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica

Martin Jakobsson a,*, John B. Anderson b, Frank O. Nitsche c, Richard Gyllencreutz a, Alexandra E. Kirshner b, Nina Kirchner d, Matthew O’Regan e, Rezwan Mohammad a, Björn Eriksson a

a Department of Geological Sciences, Stockholm University, 106 91 Stockholm, Sweden
b Department of Earth Sciences, Rice University, Houston, TX 77005, USA
c Lamont-Doherty Earth Observatory of Columbia University, Route 9 W, Palisades, NY 10964, USA
d Department of Physical Geography and Quaternary Geology, Stockholm University, 106 91 Stockholm, Sweden
e School of Earth and Ocean Sciences, Cardiff University, Wales, United Kingdom

Abstract

Pine Island Glacier drains portions of the West Antarctic Ice Sheet into the Amundsen Sea. During the Last Glacial Maximum the glacier extended nearly 500 km from its present location onto the outer continental shelf. Unusually restricted sea-ice cover during the austral summer of 2010 allowed for a systematic multibeam swath-bathymetric and chirp sonar survey of the mid-shelf section of Pine Island Trough. The mapped glacial landforms reveal new information about the paleo-Pine Island Ice Stream’s dynamic retreat from the mid-shelf area and confirm previous suggestion of a retreat in distinct steps. The periods of grounding line stability during the overall retreat phase are marked by sediment accumulations, i.e. grounding zone wedges. These wedges are here mapped in sufficient detail to characterize spatial dimensions and estimate the volume of deposited sediment. Considering a range of sediment flux rates from the paleo-Pine Island Ice Stream we estimate that the largest and most clearly defined grounding zone wedge, located at about 73°S in the surveyed area, took between 600 and 2000 years to form. The ice stream retreated landward of this wedge before 12.3 cal ka BP. The swath-bathymetric imagery of landforms in Pine Island Trough includes glacial features that suggest that retreat between periods of grounding line stability may be associated with episodes of ice shelf break-up. The depths of grounding line wedges decrease in a landward direction, from 740 to 670 m, and record elevation of the grounding line as it stepped landward. In all, the grounding line elevation varied by only ~80 m over a distance of just over 100 km, implying a low ice shelf break-up. The depths of grounding line wedges decrease in a landward direction, from 740 to 670 m, and record elevation of the grounding line as it stepped landward. In all, the grounding line elevation varied by only ~80 m over a distance of just over 100 km, implying a low ice shelf break-up. Finally, we revisited seismic reflection profile NB9902, acquired along Pine Island Trough in 1999, in combination with the newly acquired swath-bathymetric imagery from 2010. Together these data show that the ice stream paused during its retreat to form grounding zone wedges at an area in central Pine Island Trough where a high in dipping bedrock strata exists and the glacial trough is narrow, forming a bathymetric “bottle neck”.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

The West Antarctic Ice Sheet (WAIS) comprises approximately 10% of the entire Antarctic Ice Sheet volume (Lythe et al., 2001). It is an ice sheet with its base mainly grounded below sea level, making it particularly sensitive to environmental change and potentially unstable. Sea level would rise more than 3 m if the marine-based part of WAIS disintegrated (Bamber et al., 2009). Slightly less than two thirds of WAIS drains into the Ross and Ronne-Filchner Ice shelves while the remaining part drains into the Amundsen Sea through Pine Island and Thwaites glaciers (Fig. 1) (Rignot et al., 2008). These latter two glaciers were considered by Hughes (1981) as the WAIS “weak underbelly”, referring to their direct exposure to the ocean and lack of protective physiographic barriers or large buttressing ice shelves. In addition, the bedrock of these glaciers deepens significantly inland, adding to their vulnerability (Holt et al., 2006; Vaughan et al., 2006). Recent observations indeed show rapid thinning and near constant acceleration of the Pine Island Glacier (PIG) (e.g. Joughin et al., 2003). The thinning is suggested to be caused by intrusion of warmer ocean water beneath the relatively small ice shelf in front of the grounded glacier (Jenkins et al., 2010; Jacobs et al., 2011). Inflow of warmer water has recently also been documented west of Pine Island Bay

* Corresponding author. Tel.: +46 8 16 4719, E-mail address: martin.jakobsson@geo.su.se (M. Jakobsson).
(PIB) in the glacial trough offshore of western PIB and Getz and Dotson ice shelves (Walker et al., 2007; Wåhlin et al., 2010). The current behavior of the PIG highlights the need to better understand its grounding line retreat history; how fast has it retreated since the Last Glacial Maximum (LGM) and what are the main drivers of rapid retreat?

There is now compelling geomorphic and chronostratigraphic evidence for the WAIS having extended across the outer continental shelf during the LGM (Anderson et al., 2002; Lowe and Anderson, 2002; Ó Cofaigh et al., 2002; Evans et al., 2006; Hillenbrand et al., 2009; Mosola and Anderson, 2006; Smith et al., 2011). In the Amundsen Sea, the present shelf bathymetry is dominated by cross-shelf glacial troughs (Evans et al., 2006; Nitsche et al., 2007) marking the paths of former ice streams that advanced across the shelf during past glacial maxima (Lowe and Anderson, 2002; Graham et al., 2010a). One of these troughs is the Pine Island Trough (PIT) (Fig. 1). Here, the Pine Island ice stream extended to the continental shelf edge and delivered water-saturated sediments generating turbidity currents that formed gully-channel systems on the uppermost continental slope (Dowdeswell et al., 2006a). This implies that the Pine Island Glacier extended more than 500 km from its present position during LGM (Lowe and Anderson, 2002; Graham et al., 2010b). One of these troughs is the Pine Island–Thwaites Trough (PIT) (Fig. 1). Here, the Pine Island ice stream extended to the continental shelf edge and delivered water-saturated sediments generating turbidity currents that formed gully-channel systems on the uppermost continental slope (Dowdeswell et al., 2006a). This implies that the Pine Island Glacier extended more than 500 km from its present position during LGM. The central part of PIT has been sparsely mapped due to persistent sea-ice cover (Nitsche et al., 2007), although sets of grounding zone wedges were identified previously, marking still-stands in the ice retreat from the LGM position (Lowe and Anderson, 2002; Graham et al., 2010a) (Fig. 1). Prior to now, few constraints on the dynamics of the retreat history existed. Based on 14C-dates of calcareous foraminifera retrieved from sediment cores, Lowe and Anderson (2002) suggested that the ice retreated from the outer shelf before 16 ka (14C yr), but halted at about the latitude of Burke Island where it remained long enough to produce a massive grounding zone wedge (Fig. 1).

The Oden-Southern-Ocean 2009/2010 (OSO0910) expedition with Swedish icebreaker IB Oden carried out swath-bathymetric mapping, chirp sonar profiling, oceanographic station work and coring in Pine Island Trough. Since the trough area was virtually ice-free in the austral summer of 2010, the swath-bathymetric mapping and chirp sonar profiling were conducted as a systematic survey covering 4140 km2 of the mid-shelf section of the PIT (Fig. 1). Here we present the detailed bathymetric data and chirp sonar profiles along with a previously acquired seismic reflection profile that provide new insights into the glacial dynamics during the deglaciation of the continental shelf. The landforms imaged in PIT indicate stepwise retreat of Pine Island Ice Stream from the mid-shelf that was punctuated by periods of grounding line stability and minor advance followed by episodes of rapid retreat. This is similar to episodic retreat of ice streams in a number of Antarctic and Arctic cross-shelf troughs (Dowdeswell et al., 2008). Complementary to the geomorphic results presented here, Kirshner et al. (submitted for publication) provide new age constraints and sedimentary evidence for the changing glacial setting during grounding line retreat. These independent data sets support episodic post-LGM grounding line retreat within central PIT between 16.4 and 12.3 k cal yr BP.
2. Materials and methods

2.1. Multibeam swath-bathymetric mapping

The swath-bathymetric data presented in this work were collected using a hull-mounted Kongsberg 12 kHz EM122 1° × 1° multibeam echo sounder. This multibeam system includes a Seatex Seasat 200 unit for integration of GPS navigation, heading and attitude information. The motion sensor consists of Seatex’s MRU5. EM122 is capable of producing 432 beams per ping and apply multiplexing in the intermediate water depths. This implies that the transmit fan is duplicated after a small offset in along track tilt resulting in a doubling of ping density. Due to the ice protection of the EM122 transceivers, the useable across-track angular coverage is reduced to less than 65° × 65° resulting in a swath-width of typically three-four times the water depth. The favorable ice conditions during our survey allowed swath mapping of the central part of PIT along a regular survey track (Fig. 1). This has not previously been possible due to severe sea-ice conditions in this part of the bay (e.g. Evans et al., 2006; Graham et al., 2010a). Line density was maintained with a swath overlap between about 30 and 100%. Sound velocity control was achieved through regular CTD (Conductivity, Temperature, Depth) stations supplemented with XCTD (Expendable CTD), XBT (Expendable Bathy Thermograph) and XSV (Expendable Sound Velocimeter) casts. During the 12 day-long survey in PIT, 46 stations with sound velocity control were acquired. All data were processed using the software Fledermaus and gridded to a horizontal resolution of 20 × 20 m. Seafloor morphology was interpreted in the 3D environment of Fledermaus and maps were subsequently produced in the GIS software Geomedia Professional.

2.2. Chirp sonar sub-bottom profiling

The IB Oden sub-bottom profiler is a SBP 120 3° × 3° chirp sonar integrated with the multibeam through the use of the same receiving array and the capability of using the multibeam center beam to automatically adjust the acquisition window. During the OS00910 survey the chirp sonar was operated continuously using a 2.5–7 kHz and 35 ms long pulse. The ping interval was set to a fixed rate of 500 ms in order to facilitate post-processing of acoustic water column data acquired with the EM122 for physical oceanographic studies. Further information about the chirp sonar settings is found in the OS00010 cruise report (Anderson and Jakobsson, 2010).

2.3. Seismic reflection profiling

The seismic reflection profile used in this study was collected during a 1999 austral summer cruise (NBP9902) of the RV Nathaniel B. Palmer. Parts of the profile were published by Lowe and Anderson (2002, 2003). A 210 in² GI air gun was used as a seismic source and a single-channel streamer was used as a receiver. The data were recorded with an Elics seismic acquisition system and band-pass filtered. The vertical resolution of the seismic profile is on the order of 10 m. Henceforth, the full seismic profile is referred to as Line NBP9902 (Fig. 1).

3. Results

Several types of sedimentary landforms were produced when the ice sheet was grounded in PIT during the LGM and the subsequent retreat. Because sedimentation rates have been very low since ice sheet retreat, these landforms are expressed in detail in the seafloor morphology (Fig. 2). The relatively high resolution of our multibeam swath bathymetry and pristine condition of these features allows us to describe them in detail and to interpret their mode of formation and significance to ice dynamics during recession. Fig. 3 shows all identified landforms and their relationship to each other. These relationships will be further discussed after the individual landforms are described.

3.1. Grounding zone wedges

Sedimentary wedges, or grounding zone wedges (GZW), that occur within troughs on the Antarctic continental shelf are interpreted to represent grounding line deposits formed during pauses in ice sheet’s retreat from the continental shelf (Bart and Anderson, 1996; Anderson, 1999; Mosola and Anderson, 2006; Dowdeswell et al., 2008). Their occurrence within troughs that typically occur seaward of modern ice streams and association with mega-scale glacial lineations and “soft” water saturated till indicates that they are the products of deposition by fast-flowing ice streams (Alley et al., 1989). Larger wedges are commonly 50–100 m thick and considered to be formed by a broad range of processes, including sub-glacial sedimentation and deposition via sediment gravity flows debouching from the grounding line (Anderson, 1999; Christoffersen et al., 2010).

The occurrence of two GZWs within the central PIT was originally demonstrated by using swath bathymetry data and seismic reflection profiles (Lowe and Anderson, 2003). Subsequently, Graham et al. (2010a) constrained the location of the front of the larger GZW using data from two nearby multibeam swaths and referred to it as GZW5 (Fig. 1). In total, they identified five GZWs (GZW5–1; Fig. 1). GZW1 and 2 are located on the outer shelf and GZW3–5 within the central trough (Fig. 1). We will use the same nomenclature when further describing the GZWs that fall within our survey area.

The OS00910 survey includes the full extent of GZW3, 4 and 5 (Figs. 2–4). The data show that the seafloor morphology at GZW3 is actually comprised of a series of back-stepping transverse ridges that deepen in a landward direction (Fig. 5). These ridges were in part mapped by Graham et al. (2010a,b). However, it is difficult to exclude the possibility that these transverse ridges overly a small and morphologically subdued GZW. Together, the transverse ridges and grounding zone wedges record the changing elevation of the grounding line in a landward direction. The transverse ridges occur in water depths ranging from 720 to 740 m. GZW4 is located in 705–726 m and GZW5 in 726 to 670 m water depths. We further note that GZW5 appears to partly overly GZW4, the two wedges together spanning about 38 km along the axis of the trough (Fig. 4). GZW4 has a more subdued bathymetric expression relative to GZW5, with a maximum thickness of approximately 20 m (Fig. 4). GZW5 extends approximately 22 km along the trough axis, 12 km across the trough and has a maximum thickness of about 56 m when assuming its base at a water depth of 726 m (Fig. 4). However, the wedge width across the PIT is difficult to pinpoint as its outer edges, along the shallow sides of the trough, have been eroded by icebergs. The inferred width uses the outer trough walls as limits since it is evident that the wedge extends over the entire trough. The sediment volume of GZW5 within these horizontal constraints, calculated using the multibeam data, is approximately 12 km³.

3.2. Streamlined sub-glacial landforms

The surveyed part of PIT contains streamlined ridge-groove features that conform to the morphological description of mega-scale glacial lineations (MSGL) (Clark, 1993; Clark et al., 2003; Weller et al., 2006). Distinct sets of MSGLs occur north and south of GZW4 and 5 (Fig. 2c–e). The landward set trends about 350° parallel to the trough axis, while the seaward set trends 340°–345° and oblique to the trough axis (Fig. 3). Cross-cutting relations show that the seaward set is older than the landward set. Individual MSGLs...
can be followed for more than 15 km in both areas and range from >500 to 150 m in ridge-to-ridge width and have ridge heights of about 2 to >6 m. North of GZW5, the MSGLs are overprinted by iceberg furrows at a water depth above approximately 670 m, while south of GZW5 iceberg furrows generally overprint MSGLs to a depth of about 750 m.

3.3. Large curvilinear – linear furrows

North of GZW4, linear to curvilinear lineations occur in water depths deeper (690 and 720 m) than the MSGLs and are aligned parallel to the axis of the trough (Fig. 2b). Some furrows have more pronounced relief with >20 m ridge height. These lineations were
previously described by Jakobsson et al. (2011) and interpreted to be formed from an armada of grounded large icebergs discharged during an ice shelf break-up and likely associated grounding line retreat of the Pine Island Ice Stream. These features predate the MSGLs north of the GZW4 as indicated from cross-cutting relationships.

3.4. Iceberg plowmarks

Randomly oriented iceberg plowmarks dominate the seafloor morphology in water depths shallower than ~670 m north of GZW5 and shallower than ~750 m south of this wedge (Fig. 2). These features are generally not traceable for more than 2 km before they change directions and their relief is generally <10 m. The seabed morphology of GZW5 is also dominated by iceberg furrows and plowmarks (Fig. 4). Deep-keeled Antarctic icebergs are typically calved from fast-flowing ice streams and outlet glaciers that have only limited floating margins, whereas more extensive ice shelves often produce bergs with keels no deeper than about 300 m (Dowdeswell and Bamber, 2007).

3.5. Ridges

One of the most conspicuous geomorphic features in the area consists of extremely regular and small sedimentary ridges previously described by Jakobsson et al. (2011) and named corrugation ridges. These are 1–2 m from trough to crest and separated by about 60–200 m (Fig. 2b). Within the surveyed area, corrugation ridges are mostly constrained to the northern part of the trough (Figs. 2 and 3). However, some isolated sets of corrugation ridges occur also within the MSGLs (Fig. 3). The glacial dynamic connection between the large furrows, the corrugation ridges, and the iceberg plow ridges was interpreted by Jakobsson et al. (2011) and is further discussed below.

3.6. Transverse ridges (moraines)

The surface of GZW3 is dominated by a series of ridges with their spatial extensions transverse to the axis of PIT (Fig. 5). They range from a few meters to 6 m high and occur between a few hundred meters to >1000 m apart. Some of these ridges bend and continue along the PIT at the eastern most part of the trough, near the outer wall (Fig. 5).

3.7. Seismic stratigraphy

Seismic profile NBP9902 extends along the deepest central part of PIT in the southern section of the surveyed area (Figs. 1 and 6). From the southern part of GZW5 and northward, the seismic line continues slightly westward of the deepest part of the trough. The seismic stratigraphy of GZW5 is thus imaged along its extension in a slightly oblique angle. Fig. 6 displays the section between shot point 8100 and 1600 along with chirp sonar profile PI-125A, which is the profile most closely following NBP9902. The rest of profile NBP9902 is shown in Supplementary data. The north-dipping strata underlying the trough have been eroded by the ice sheet, resulting in a prominent unconformity that is an amalgamation of several erosion surfaces visible only on the outer shelf (Lowe and Anderson, 2002). The older strata below the unconformity dip seaward at progressively lower angles north of GZW5 and near the shelf break the strata are nearly horizontal (Supplementary data). Unfortunately, a lack of crossing lines makes it difficult to fully access the inclination of the strata and the degree to which the trough has shifted in its position on the shelf with time. GZW5 is not characterized by a specific visible acoustic layering, so it is not possible to determine if there are several wedges stacked upon one another. Landwards of GZW5 there is a very thin conformable unit visible above the unconformity. The chirp profile provides limited additional information due to poor acoustic penetration. Nevertheless, a thin (~<3 ms equivalent to ~2 m) conformable sediment drape can be distinguished in many places at closer inspection (Fig. 6d) and sediment cores confirm the existence of these surface sediments.

4. Discussion and interpretation

The landforms imaged by our survey provide a more detailed view on the WAIS retreat from the central PIT than previously revealed by
the more sparse data from the region (Lowe and Anderson, 2002; Graham et al., 2010a). Previous mapping of the outer shelf has suggested that the major PIT bifurcates into two paths, both reaching the shelf edge (Evans et al., 2006; Dowdeswell et al., 2006a). Following previous authors the two outer troughs of these ice stream pathways are henceforth referred to as PITW and PITE (Fig. 1). Considering these troughs together with previously mapped landforms, three conceptual models for the Pine Island–Thwaites paleo-ice stream flow during the LGM were presented by Graham et al. (2010a,b). Their preferred model suggests that the different flow directions recorded in the two troughs were formed at different times and that the ice stream of PITW predates that of PITE (Fig. 7). Our new data do not allow us to constrain the age of the outer shelf troughs. It is also worth noting that the sole evidence for ice sheet grounding at the shelf break is the occurrence of gullies on the upper slope, which are argued to be the product of sediment-laden water flowing from beneath the margin of the ice sheet (Anderson, 1999; Dowdeswell et al., 2006a). However, our data do reveal a complex history of grounding line retreat from the central part of the trough (Fig. 7). The mapped landforms indicate that this retreat was marked by one episode of ice shelf break-up (Jakobsson et al., 2011) while the sediment stratigraphy suggests an additional episode of ice shelf break-up (Kirshner et al., submitted for publication). Furthermore, prolonged pauses in grounding line retreat occurred that were associated with build-up of grounding line wedges, possibly ice shelf regrowth, and an episode of ice stream re-advance. The relative timing of these events is based on the depth of geomorphic features that record grounding line depths and superposition of these features.

The deepest part of the main trough north of GZW5-3 is oriented towards PITE and contains corrugation ridges (Figs. 2 and 3). These features are interpreted to have been formed during an ice shelf...
break-up and likely associated grounding line retreat (Jakobsson et al., 2011). This hypothesis implies that an ice shelf fringed the Pine Island Ice Stream while it extended across the outer-mid shelf. We cannot exclude that this ice shelf broke up in similar fashion as the Larsen A and B ice shelves in 1995 and 2002 (MacAyeal et al., 2003), although in the case of the PIB break-up, the ice shelf must have disintegrated all the way back to the grounding line and even a bit beyond as the oriented features occur in water depths down to 650 m. The mechanism for the corrugation ridge formation involves sediment being squeezed into ridges by the trailing edge of a portion of a broken-up ice shelf rising and settling to the seafloor under tidal influence as it drifts seaward (Jakobsson et al., 2011). Eventually, at a pace of 60–200 m/day, the armada of large icebergs reached the outer more shallow part of the central PIT where the icebergs grounded to form iceberg plow ridges (Fig. 2a). It should be noted that the grounding line retreat due to the ice shelf break-up was asymmetric and appears to have occurred only in the western part of the trough.

The series of landward stepping transverse ridges that occur between 720 and 740 m water depth may have been formed as the ice-stream retreated in this eastern part of the trough following the break-up of the ice shelf (Fig. 5). These small transverse ridges may be similar to De Geer moraines (Lindén and Möller, 2005). Furthermore, similar transverse ridges have elsewhere been demonstrated to be formed annually in ice contact settings (Ottesen and Dowdeswell, 2006). If the transverse ridges mapped in this work are annual formations, the average retreat rate ranged from hundreds of meters to more than 1000 m per year. Eventually this retreat stopped and a prolonged pause in grounding line retreat resulted in the formation of GZW4 when the grounding line was located at water depths...
between 726 and 706 m (Fig. 5). Evident from the MSGL north set is that this still-stand was followed by an ice stream re-advance (Figs. 3 and 8b). As the grounding line was elevated to the level of GZW4 the flow was no longer controlled by the outer trough and the ice stream was free to follow a more westward path. Notably, the Graham et al. (2010a,b) model would suggest that the ice stream would actually have followed a more easterly path as it retreated, which is not consistent with our data (Fig. 7). However, since there is no coherent data coverage and due to increasing overprinting of iceberg scours west of our survey area it is not possible to determine the extent of the re-advance. The ice stream may only have advanced over GZW4 and a little distance beyond, at least as far as we mapped the MSGL north set. From its GZW 4 location, the grounding line stepped landward to the location of GZW5, where the depth of the grounding line was elevated by deposition of the wedge to between 726 and 670 m (Fig. 8c).

The precise timing of the formation of a GZW is difficult to determine as it requires that sediment units constraining both the beginning and end of wedge formation are identified and dated. Our radiocarbon data are not sufficient to constrain the exact timing of GZW formation (Kirshner et al., submitted for publication). However, the GZW5’s morphology is mapped in detail allowing us to calculate that the wedge’s sediment volume per meter of ice-stream width is approximately \(1 \times 10^6 \text{ m}^3\), i.e. the same volume as previously concluded per meter width of GZW5 by Graham et al. (2010a,b). The volume per meter ice stream-width, together with estimations of sediment flux per year of the Pine Island and Thwaites Ice Streams, allows us to evaluate the time required to construct GZW5 and, thus, the time of one of Pine Island Ice Stream’s still-stands during its general retreat from the central trough. If we assume that the transverse moraines located on GZW3 (Fig. 5) are annual retreat features, it is possible to estimate the sediment flux of the Pine Island ice stream when it was active at this location of PIT. The three larger ridges R1-R3 range in volume from \(1260 - 1620 \text{ m}^3 \text{ m}^{-1}\) while the three smaller ones R4–R6 range from \(200 - 300 \text{ m}^3 \text{ m}^{-1}\), calculated for a 1 m wide section along profile A–B shown in Fig. 5. Thus, these ridges suggest yearly sediment fluxes of between 200 and 1620 m\(^3\) a\(^{-1}\) (meter ice stream width).

The recent study of the Kamb Ice Stream in Ross embayment suggests that sediment wedges near grounding lines in that area were formed mostly by melt out of basal debris (Christoffersen et al., 2010). Assuming different scenarios for Kamb Ice Stream’s active and stagnant phases over time and ice flow speeds between 500 m a\(^{-1}\) (active) and 0 m a\(^{-1}\) (stagnant), Christoffersen et al. (2010) calculated average sediment fluxes between 525 and 875 m\(^2\) a\(^{-1}\) m\(^{-1}\). This is within range of the sediment fluxes of about \(100-800 \text{ m}^3 \text{ a}^{-1} \text{ m}^{-1}\) estimated for the Marguerite Bay paleo-ice stream, which flowed across the western continental shelf of the Antarctic Peninsula (Dowdeswell et al., 2004). Considering that the mapped landforms in PIT all seem to suggest a highly dynamic ice stream behavior and that the geology of the outer shelf is characterized by easily eroded sedimentary strata (Anderson, 1999), low sediment fluxes near 100 m\(^3\) a\(^{-1}\) \text{ m}^{-1}\) seems unlikely. If we consider flux rates between 500 and 1650 m\(^2\) a\(^{-1}\) \text{ m}^{-1}\), it would have taken between 600 and 2000 years to form GZW5 (Fig. 9). The Pine Island Ice Stream retreated from the location of GZW5 before 12.3 cal ka BP, a timing inferred from dated foraminifera in a sediment core retrieved just landward of the wedge (Fig. 8d; Kirshner et al., submitted for publication).

A major question is why the Pine Island ice stream changed path during the re-advance that followed the ice shelf break-up, grounding line retreat and subsequent still-stand and formation of

---

**Fig. 8.** Ice retreat from the Pine Island outer and central continental shelf based on previous work and the interpreted glaciogenic features mapped in this study. Map a) shows the oldest reconstruction while d is the youngest when the ice finally withdraw from the area at about 12.3 cal ka BP.

---

Please cite this article in press as: Jakobsson, M., et al., Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica, Quaternary Science Reviews (2012), doi:10.1016/j.quascirev.2011.12.017
Fig. 9. Calculated formation time of GZW5 based on its volume and assuming sediment flux rates from the Pine Island paleo-ice stream between 500 and 1650 m$^3$ a$^{-1}$ m$^{-1}$. The range of flux rates estimated by Dowdeswell et al. (2004) and Christophersen et al., 2010 are inferred as a reference (denoted D. and Ch. respectively).

GZW4? Even if the re-advance was minor, it still changed the flow path as evident from the MSGL north set (Fig. 3).

It has been suggested that trough morphology and underlying geology influence ice stream flow (Dowdeswell et al., 2006b). The one available seismic profile (NB99902) does not provide a clear answer to whether the geology in PIB could have influenced ice stream behavior (Fig. 6). However, the locations of GZWs 5–3, and thus the location for grounding line stability, do coincide with a high in the dipping strata that may indicate more resistant layers, and thus suggests that this may constitute an area of greater bed resistance to the ice stream flow. In addition, both GZW4 and GZW5 occur in locations of ‘bottle-necking’ in the trough. This, plus the fact that lineation direction occurs at a location where the trough orientation changes, highlights the importance of trough bathymetry on ice stream flow direction.

5. Conclusions

In conclusion, the glacial retreat from the mid-shelf section of PIT was highly dynamic, involving both ice shelf break-up and associated grounding line retreat. The retreat appears to have been episodic in accordance with typical retreat behavior previously suggested for the last deglaciation of polar continental shelves (Dowdeswell et al., 2008). The ice retreated from the mid-shelf section of PIT first at about 12.3 cal ka BP to a location southward of our surveyed area. This landward grounding line location was likely coincident with an underlying bedrock change from seaward dipping sedimentary strata to crystalline bedrock, which has been shown to be the location of a notable change in glacial landforms (Lowe and Anderson, 2002, 2003). The depths of grounding line wedges decrease in a landward direction, from 740 to 670 m, and record elevation of the grounding line as it stepped landward. In all, the grounding line elevation varied by only ~80 m over a distance of just over 100 km, likely implying a low ice sheet profile. The calculated volume of GZWS suggests that the grounding line in the mid-shelf section of PIT was stable, before it finally retreated from the area, during a time period between about 600 and 2000 years if sediment flux rates between 500 and 1650 m$^3$ a$^{-1}$ m$^{-1}$ are considered.

Acknowledgment

The expedition OS0910 was carried out as collaboration between Swedish Polar Research Secretariat, the Swedish Research Council and the US National Science Foundation (NSF). We thank the Captain and Crew of the IB Oden. Financial support was received from the Swedish Research Council (VR), the Swedish Royal Academy of Sciences through a grant financed by the Knut and Alice Wallenberg Foundation and the Bert Bolin Centre for Climate Research at Stockholm University. E. Nitsche was supported by NSF grant ANT-0838735 and Anderson by NSF/ARRA grant ANT-0837925. We thank one anonymous reviewer and Alastair Graham for insightful comments that improved the manuscript.

Appendix. Supplementary data


References