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Are Antarctic Peninsula Ice Sheet grounding events manifest in sedimentary cycles on the adjacent continental rise?

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Abstract

The direct record of Late Miocene–Early Pliocene Antarctic Peninsula Ice Sheet expansions from a previously published seismostratigraphic study of the outer shelf at Ocean Drilling Program Site 1097 is compared to the glacial history we deduced from published proxy evidence within coeval sections on the adjacent continental rise. The proxies are sedimentary structures (laminated vs. massive/bioturbated facies) and clay minerals (predominantly smectite and chlorite contents) from Ocean Drilling Program Site 1095 located on the distal part of a large drift. The comparison shows that more sedimentary cycles are evident on the continental rise for three of the four diatom biozones we considered. This indicates that the continental-rise sedimentology may indeed be related to local or regional paleoenvironmental variability, including Antarctic Peninsula Ice Sheet grounding events on the adjacent outer continental shelf. If correct, this would be a promising result because unlike the outer continental shelf sequences drilled thus far, the continental rise record is relatively continuous and can be dated using paleomagnetic and biostratigraphic data. However, our study also shows that no objective criteria provide direct linkages between the glacial history we deduced from the two continental rise proxies and that previously derived from the continental-shelf seismic stratigraphy. Furthermore, the two sedimentologic proxies on the continental rise do not always provide a consistent picture of glacial history when compared against each other.

Keywords: Antarctic Peninsula; glaciations; sedimentary cycles; grounding events; Late Miocene; Early Pliocene

1. Introduction

Proxy evidence from low-latitude settings, such as oxygen isotope records (e.g., Shackleton and Kennett, 1975; Shackleton and Opdyke, 1976; Shackleton and Hall, 1984; Zachos et al., 2001) and sea-level curves (e.g., Haq et al., 1987; Mitchum et al., 1994; Miller et al., 2005), provide the most detailed view of global climate changes. In contrast to proxy-based approaches to global-scale changes, reconstructing detailed high-resolution Antarctic glacial history from direct evidence for a specific site is extremely problematic because the deposits and seafloor morphology created during a cycle of ice sheet advance and retreat can be removed during subsequent cycles (e.g., Birkenmajer, 1991). In addition,

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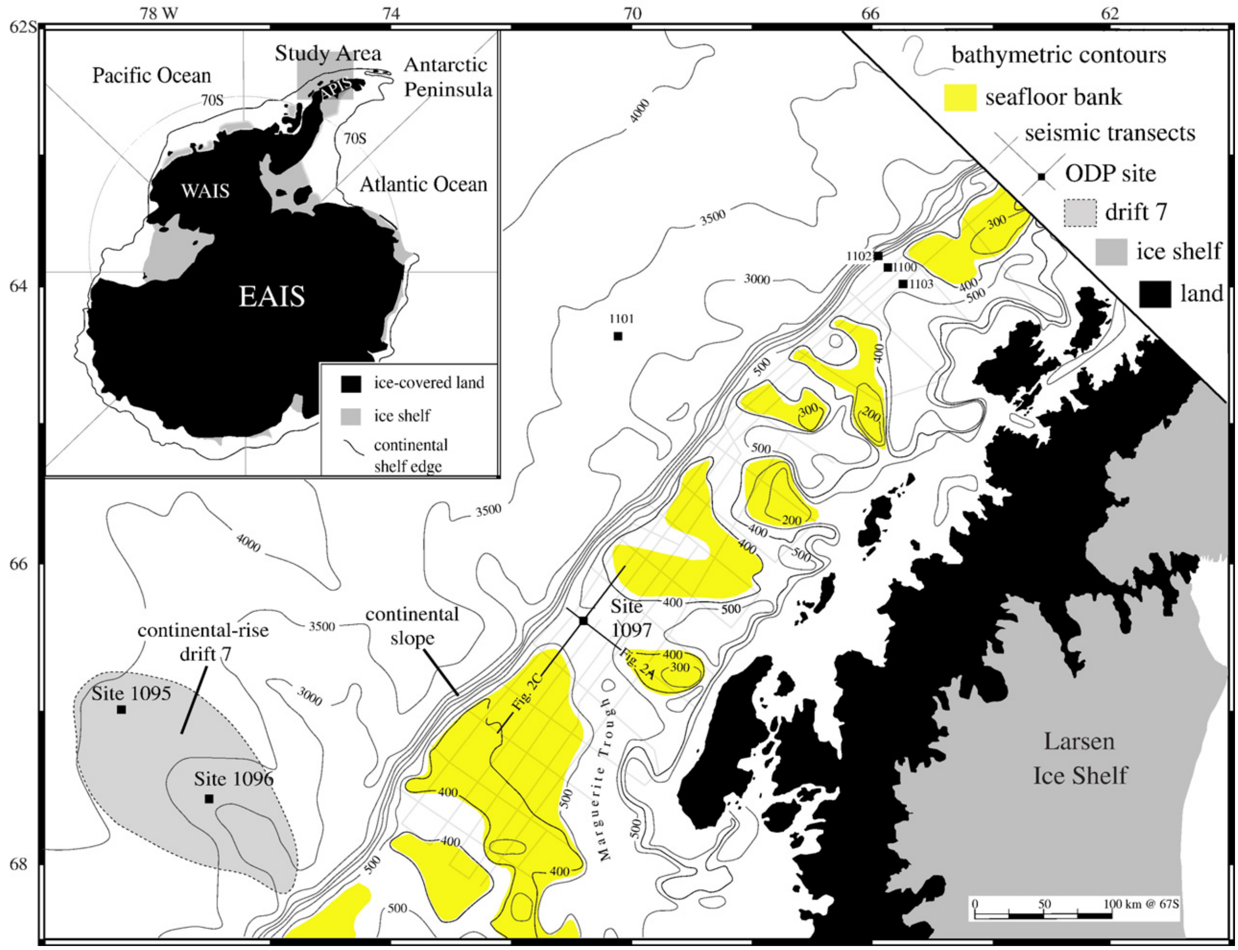

Fig. 1. Antarctic Peninsula Pacific-margin bathymetry (contours in meters below sea level from Rebesco et al., 1998), location of seismic profiles and ODP Leg 178 sites. The shaded areas on the continental shelf correspond to shallow banks whereas unshaded areas correspond to troughs indicating the locations of grounded ice streams during the last glacial period. The main discharge corridor of the APIS was at Marguerite Trough. Bold lines show the locations of seismic profiles shown in Fig. 2A and B. The shaded area on the continental rise (lower left hand side) depicts the location of Drift 7. The inset shows the position of APIS with respect to the entire continent. EAIS = East Antarctic Ice Sheet. WAIS = West Antarctic Ice Sheet.

dating the Antarctic deposits is problematic because of the virtual lack of calcareous microfossils and the common occurrence of reworking of siliceous microfossils (e.g., Barrett, 1996). Given the inability to know what might be missing from proximal glacial settings, some investigators have sought higher-resolution glacial-history data from deep-water settings immediately beyond the regions affected by subglacial erosion (e.g., Tucholke et al., 1976; Barker and Camerlenghi, 2002; Gruetzner et al., 2003; Cooper and O'Brien, 2004). The challenge is to find a continuous, datable and high-resolution sedimentary record close enough to the continent that the adjacent region's glacial history can be unambiguously interpreted irrespective of other processes that may not be linked to ice sheet dynamics. One possible deep-water location meeting this criterion is the Antarctic continental rise (Kuvaas and Leitchenkov, 1992; Tomlinson et al., 1992; McGinnis and Hayes, 1995; Rebesco et al., 1996, 1997; Barker et al., 1998; Barker and Camerlenghi, 2002; Cooper and O'Brien, 2004; Rebesco et al., 2006). Thus far, continental rise drifts[1] have been drilled on the Antarctic Peninsula and Prydz Bay margins during Ocean Drilling Program (ODP) Legs 178 (Barker and Camerlenghi, 2002) and 188 (Cooper and O'Brien, 2004),

[1] Drifts on the Antarctic Peninsula continental rise do not fit into any of the three drifts types described by Faugeres et al. (1993). Construction of the Antarctic Peninsula drifts results from a long-lived interaction between down-slope turbidity currents (derived from unstable slope sediments) and deep bottom currents moving re-suspended sediment along the strike of the continental rise (Barker and Camerlenghi, 2002; Rebesco et al., 2002).

respectively. If there are genetic links between grounding events on the continental shelf and processes/products on the continental rise (e.g., Hepp et al., 2006), then a comparison of the corresponding geologic records should reveal some similarities in the glacial histories. In this study, we revisit the marine sedimentary record of the Antarctic Peninsula Ice Sheet (APIS). Several studies have shown that APIS grounding events (i.e., expansion and contraction of ice in contact with the seafloor) that affected the outer continental shelf during the Late Quaternary (e.g. Pope and Anderson, 1992; Dowdeswell et al., 2004; Ó Cofaigh et al., 2005) are also preserved in the continental rise sedimentary record (e.g. Pudsey and Camerlenghi, 1998; Lucchi et al., 2002). The purpose of our study is to test this relationship for the Late Miocene and Early Pliocene via a comparison between a previous interpretation of glacial history derived from the seismostratigraphy on the outer continental shelf (Bart et al., 2005) and a glacial history we deduced from sedimentary proxies reported from continental rise sediments (Hillenbrand and Ehrmann, 2002; Pudsey, 2002a,b). In particular, we ask the following question: Can drift sedimentology on the Antarctic continental rise be uniquely related to major grounding events known from the adjacent outer-continental-shelf stratigraphy?

2. Materials and methods

In this study, we focused on results from ODP Leg 178 because detailed analyses of the Antarctic Peninsula continental-shelf and continental-rise stratigraphy have already been independently conducted for this region. On the continental shelf, we used the most-recent characterization of Late Miocene to Early Pliocene (7.94 to 5.12 Ma) APIS grounding events by Bart et al. (2005) because their study relied on a regional seismic data set with multiple strike- and dip-oriented transects, which were correlated with the lithostratigraphic and chronostratigraphic record at Site 1097 on the continental shelf (Figs. 1 and 2). ODP Site 1097 is located on the outer continental shelf at 66°23.5680’ S, 70°45.3841’ W and was drilled to a depth of 436.60 m at a water depth of 552 m. Fifty-one cores were taken at the site with a total recovery of 59.30 m (~14% recovery). Bart and Anderson (1995) defined four packages which exhibit distinct stratal geometries. In particular, Package-3, the Late-Miocene to Early-Pliocene section, is the third package down from the seafloor surface and exhibits an overall progradational stacking pattern. The two-way travel times (TWTTs) for the top of seismostratigraphic Package-3 and the nine seismic reflectors of Package-3 at Site 1097 (interpreted as glacial unconformities by Bart and Anderson, 1995) were measured in milliseconds below the seafloor (ms bsf). The time was converted to subbottom depth by using velocity data reported for Site 1097 (Shipboard Scientific Party, 1999a). Age control for Package-3 unconformities on the continental shelf was based on diatom biozones at Site 1097 described by Iwai and Winter (2002) (Fig. 2). The age model for Site 1097 is corroborated by post-cruise studies of radiolarian biostratigraphy (Lazarus, 2002), $^{40}Ar/^{39}Ar$ dating of volcanic clasts (Di Vincenzo et al., 2002), and strontium dating of barnacle shells from Package-3 strata sampled at Site 1103 (Lavelle et al., 2002), which is located on the shelf to the northeast of Site 1097 (Fig. 1).

ODP Site 1095 is located on the continental rise at 66°23.5680’ S, 70°45.3841’ W and was drilled to a depth of ~560 m composite depth (mcd) at a water depth of 3840 m. Within the depth interval of interest (165 to 345 mcd), core recovery was 89%. At Site 1095, which is located on the distal part of Drift 7 (as defined by Rebesco et al., 1996) on the continental rise west of the Antarctic Peninsula (Fig. 1), we used the alternations between massive/bioturbated and laminated sediments (Shipboard Scientific Party, 1999b; Pudsey, 2002b), and between two different clay-mineral assemblages (Hillenbrand and Ehrmann, 2002) as proxies for glacial–interglacial cyclicity. On the bases of these previous studies (e.g., Pudsey, 2002b; Hillenbrand and Ehrmann, 2002), we interpreted bioturbated/massive sediments enriched in smectite as interglacial deposits and laminated sediments enriched in chlorite as glacial deposits. We determined the depth ranges of the same diatom biozones at Site 1095 (described by Winter and Iwai, 2002) which were also drilled at Site 1097. Next, we noted the position of laminated versus bioturbated/massive sediments as well as the position of clay-mineral cycles with respect to the diatom biozones at Site 1095. Based on this information, we assigned a numbering scheme for the glacial–interglacial cycles that we independently inferred from these proxies. The glacial cycles for each data type were counted from the top of a diatom biozone downwards. We constructed a chart showing how seismostratigraphic evidence on the continental shelf compares with the proxy evidence on the continental rise (Fig. 3; discussed later). Both continental shelf and continental rise data are reported with respect to the same diatom biozones described for Site 1097 (Iwai and Winter, 2002) and for Site 1095 (Winter and Iwai, 2002). Age control for Site 1095 is further constrained by magnetostratigraphy (Acton et al., 2002).

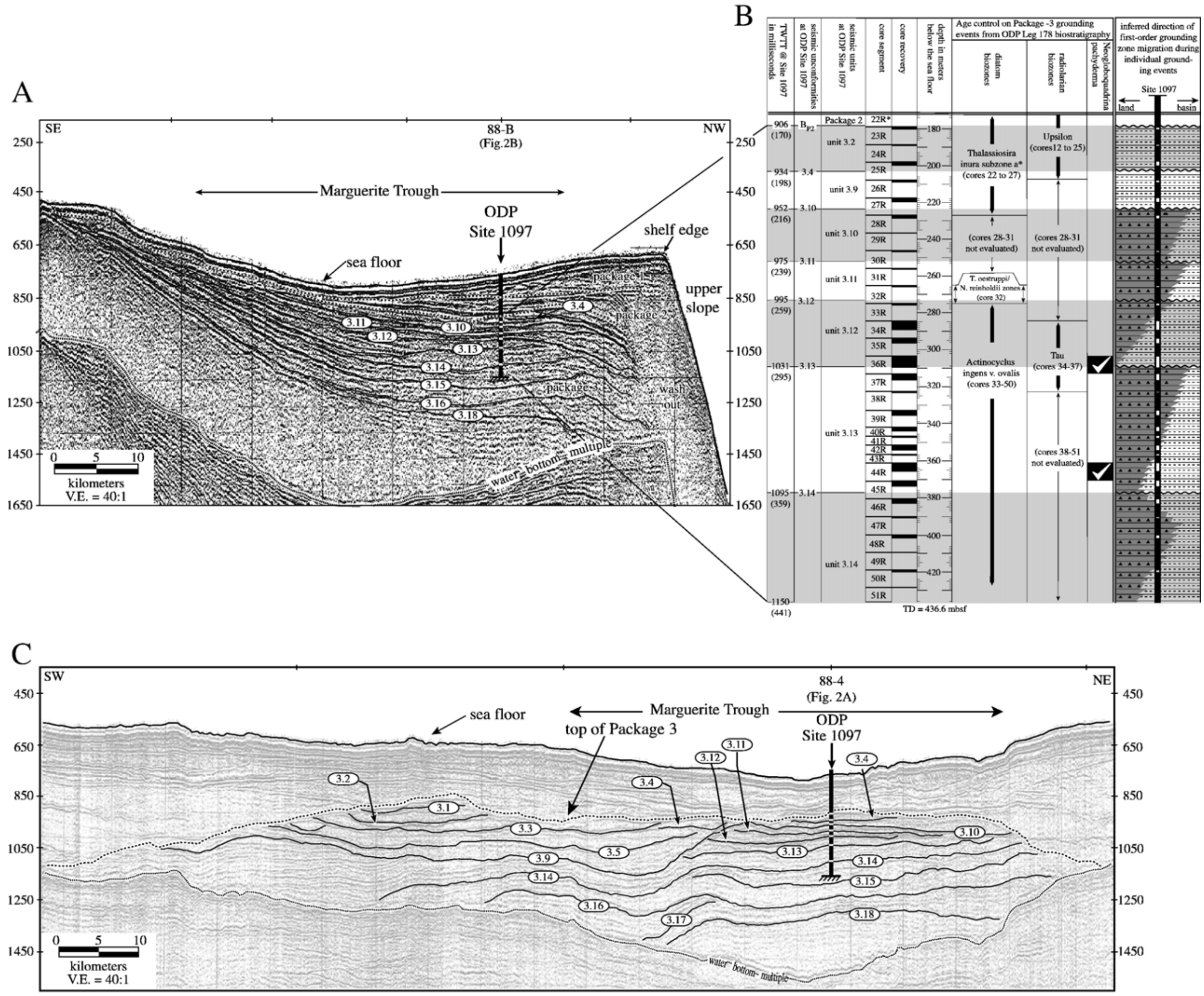

Fig. 2. A.) Dip-oriented seismic profile 88-4 crossing an inner shelf bank Marguerite Trough, and ODP Site 1097 on the outer continental shelf. The numbered black lines correspond to seismic reflectors in seismostratigraphic Package-3 that were interpreted by Bart and Anderson (1995) to be subglacial erosional unconformities. Six of the Package-3 unconformities are penetrated at Site 1097. B.) The chart shows the correlation of Package-3 unconformities to diatom biozones described by Iwai and Winter (2002) for Site 1097. Radiolarian biozones (Lazarus, 2002) and the occurrence of the planktic foraminifer *Neogloboquadrina pachyderma* sin. are also shown. A column to the right shows the inferred directions of APIS grounding zone migrations (Bart et al., 2005). The dark shaded sections with triangles represent units interpreted to be subglacial sediments whereas the horizontal dashed sections correspond to proglacial sediments (Eyles et al., 2001). At the vertical bar in the center of the column (marked with Site 1097), the drilled sections with core recovery are shown in white. C.) Strike-oriented seismic profile 88-B crossing Marguerite Trough on the outer continental shelf at Site 1097. Numerous cross cutting stratal relationships are evident in the strike sections on the outer continental shelf. The regional strike-view shows that additional reflectors (labeled 3.1, 3.2, 3.3) are found below the base of Package 2 and above unconformity 3.4. Likewise, other Package-3 reflectors from this sector of the continental shelf (labeled 3.5, 3.8 and 3.9) are constrained to have formed between reflectors 3.4 and 3.10. Reflectors 3.15 to 3.18 are below the bottom hole depth at Site 1097.

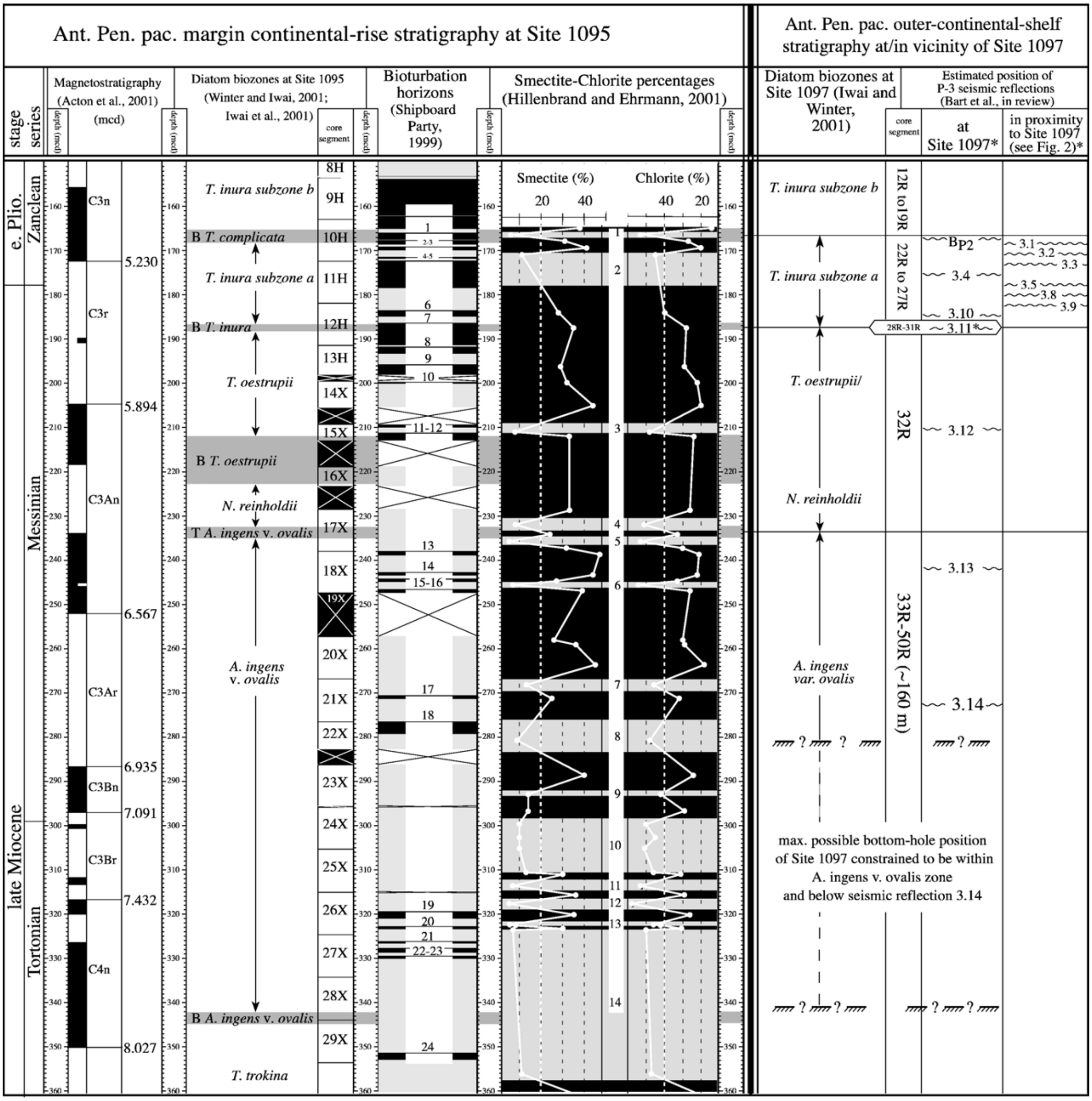

Fig. 3. The continental rise diatom biostratigraphy, sedimentary structures and clay mineralogy at Site 1095 compared to the diatom biostratigraphy and seismostratigraphy on the continental shelf at Site 1097. The biozones of interest are *T. inura* (subzone a), *T. oestrupii*, *N. reinholdii*, and *A. ingens* v. *ovalis*. Laminated sections at Site 1095 presumably corresponding to turbidites associated with grounding events on the shelf during glacial periods are shown in gray. Bioturbated and massive sediments at Site 1095 presumably corresponding to interglacial condensed sections are shown in black. The white zones marked with an x correspond to depths of no core recovery. Twenty-four cycles of sedimentary structures are observed. The depths at which the 44 clay mineralogy analyses were conducted are shown by the white dots connected with the white line. Based on the two end-member ratios described by Hillenbrand and Ehrmann (2002), we deduced a minimum of 14 clay mineral cycles. The black shaded intervals correspond to clay-ratios presumably associated with interglacial periods and the gray shaded intervals correspond to clay mineral-ratios presumably associated with glacial periods. The right column of the chart shows the estimated position of unconformities within seismostratigraphic Package-3 on the continental shelf with respect to the diatom biozones at Site 1097. Based on regional seismic stratigraphic results, seven APIS grounding events are represented at Site 1097 during the Late Miocene and Early Pliocene. The seismic correlation within the larger Marguerite Trough area (see Fig. 2C) shows that an additional six grounding events also affected the outer continental shelf. Thirteen grounding events are evident in the regional seismic stratigraphy from the outer continental shelf.

3. Results

3.1. The seismic stratigraphy on the Antarctic Peninsula outer continental shelf and its correlation with Site 1097

3.1.1. Surface and subsurface evidence of APIS grounding events

During the current interglacial, grounded ice, i.e., ice in contact with the seafloor, is confined to bays and fjords but many lines of morphological, geological, and geophysical evidence indicate that grounded ice advanced to the shelf edge during the last major expansions of grounded ice around the Antarctic Peninsula (e.g., Heroy and Anderson, 2005; Ó Cofaigh et al., 2005). Wide foredeepened troughs mark the sites of ice streams, zones of fast flowing ice that extended across the continental shelf during previous glacial periods (e.g., Canals et al., 2000, 2003; Dowdeswell et al., 2004; Amblas et al., 2006). In the subsurface, seismic reflectors exhibiting trough-like geometry, foreset truncation, regional extent (several tens of kilometers) and crosscutting relationships between underlying and overlying units are interpreted as unconformities eroded by grounded ice (Larter and Barker, 1989; Pudsey et al., 1994; Vanneste and Larter, 1995; Bart et al., 2005). Chaotic seismic facies and/or truncated foreset reflections directly below these unconformities generally are interpreted as proglacial strata that were truncated as the ice sheet advanced across the continental shelf.

The first major seismic-based study of APIS glacial history from the perspective of the outer continental shelf stratigraphy was conducted by Larter and Barker (1989) who reported evidence for eight major grounding events. Using a denser grid of higher resolution single channel seismic data, Bart and Anderson (1995) proposed that there were thirty-one major grounding events. The recent drilling confirmed that the sedimentary sequence of the shelf is indeed composed of glaciogenic sediments including subglacially deposited tills (Barker and Camerlenghi, 2002). Along with the available age control, the glacial deposits drilled at the ODP Leg 178 sites on the continental shelf indicate that ice was periodically grounded on the shelf since at least ~10 My, i.e., the Late Miocene (Barker and Camerlenghi, 2002). Bart et al. (2005) correlated regional seismic reflectors interpreted as glacial unconformities with published lithological and chronological data from Sites 1097 and 1103. Because of the higher core recovery in deeply buried diamictites (16.7%) than in the overlying soft matrix diamicts (9%), Bart et al. (2005) focused on the evidence for grounding events in seismic Package-3 of Bart and Anderson (1995).

Table 1
Number of Late Miocene/Early Pliocene glacial cycles inferred from A.) the outer continental shelf (OCS) seismic stratigraphic grounding events (at/or in the vicinity of ODP Site 1097); B.) Continental-rise (CR) drift cycles of sedimentary structures at Site 1095; and C.) Continental-rise (CR) drift cycles of clay minerals (smectite and chlorite) at Site 1095 with respect to D.) Diatom biozones, timing and zone durations at CR Site 1095 and OCS Site 1097

A. OCS seis. strat. grounding events at/near Site 1097 (Bart et al., 2005)	B. CR drift cycles of sed. struct. at Site 1095 (Pudsey, 2002b; Shipboard Scientific Party, 1999b)		C. CR Clay mineral cycles at Site 1095 (Hillenbrand and Ehrmann, 2002)		D. Diatom biozones at Site 1095 (CR)/1097 (OCS) and timing and zone duration (Ma) based on max. ranges of diatom biozone at Site 1095 (Iwai et al., 2002)			
8	6		2		*Thalassiosira inura* (subzone a)	5.12 to 5.55	0.43	
2	5	6	1	2	*Thalassiosira oestrupii*	5.55 to 6.12	0.57	0.72
	1		1		*Nitschia reinholdii*	6.12 to 6.27	0.15	
2	12		10		*Actinocyclus ingens* var. *ovalis*	6.27 to 7.94	1.67	

3.1.2. Grounding events during the deposition of seismic Package-3 at Site 1097

According to the regional seismostratigraphy by Bart et al. (2005), only seven units of seismic Package-3 were cored at Site 1097 (Units 3.2, 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14; see Fig. 2). These seven units correspond to cores 23R to 51R and are bound by seismic reflectors interpreted to be glacial unconformities (Unconformities BP2[2], 3.4, 3.10, 3.11, 3.12, 3.13 and 3.14). At Site 1097, five of these seven Package-3 units (Units 3.10, 3.11, 3.12, 3.13 and 3.14) contain sediments that Eyles et al. (2001) interpret to be subglacial tills which strongly supports the Bart and Anderson (1995) glacial-unconformity interpretation of Package-3 reflectors. If the Bart and Anderson (1995) glacial-unconformity interpretation of the other seismic reflectors is accepted, then the cross-cutting stratigraphic relationships (Fig. 2A/C) require that at least an additional six APIS grounding events occurred within the timeframe represented by cores 23R to 51R. For example, stratigraphic super-position shows that Unconformities 3.1, 3.2 and 3.3 are below Unconformity BP2 and above Unconformity 3.4. Therefore, based on the regional seismic framework, grounding events associated with reflectors 3.1, 3.2, 3.3, 3.5, 3.8 and 3.9 also occurred during the Package-3 timeframe in question[3]. According to detailed diatom biostratigraphy (Iwai and Winter, 2002), Package-3 strata cored at Site 1097 span four diatom biozones (i.e., *Actinocyclus ingens* var. *ovalis*, *Nitzschia reinholdii*, *Thalassiosira oestrupii*, and *Thalassiosira inura* (subzone a); see Fig. 2B) corresponding to the Late Miocene to Early Pliocene. The regional seismic stratigraphic framework indicates that a minimum of twelve APIS grounding events occurred on the outer continental shelf during the Package-3 time interval represented at Site 1097. Based on this combination of seismic stratigraphic evidence with diatom-biozone age control, we conclude that at least two grounding events occurred during the time spanning the *A. ingens* var. *ovalis* biozone. Two grounding events occurred during the time interval defined by the *T. oestrupii*/*N. reinholdii* biozone[4] whereas at least eight Package-3 grounding events occurred during the time period corresponding to the *T. inura* biozone (Table 1).

[2] B_{P2} corresponds to the base of Package 2 as defined by Bart et al. (2005).

[3] Bart et al. (2005) show that the stratigraphic evidence for grounding events 3.6 and 3.7 is found far to the northeast and cannot be directly correlated to units and unconformities observed at Site 1097. In other words, since grounding events associated with Unconformities 3.6 and 3.7 might be correlative with the other

[4] Unconformity 3.11 is located between core segments 28R to 31R. These segments are not assigned to a biozone. For the purpose of this study, we arbitrarily assign Unconformity 3.11 to *T. oestrupii*/*N. reinholdii* biozone.

3.2. Sedimentary cycles at Site 1095 on the continental rise

3.2.1. Grounding-events deduced from alternations between laminated and bioturbated/massive sedimentary units

At Site 1095, the sedimentary sequence coeval to seismic Package-3 on the shelf (see column B in Fig. 3) is 180 m thick and spans cores 8H to 29X. The section is characterized by thick sequences of greenish gray silt and mud. The sequence is dominated by sharp-based, graded, variably laminated, fine sands/silts, and laminated silty clays (collectively shown with a gray shade in column C of Fig. 3). The laminated facies is distinguished by the presence and abundance of very fine sand and silt laminae. These units are similar to those interpreted as muddy sediment gravity flows deposited in deep-sea environments (e.g., Stow and Piper, 1984; Pickering et al., 1988). Laminated sediments at Site 1095 presumably represent down-slope turbidite deposition when grounded ice advanced to the outer continental shelf and delivered large volumes of terrigenous detritus to the adjacent continental slope (Pudsey, 2002b). During shelf-edge grounding events, the ice sheet “bulldozed” subglacial debris across the shelf break down to the steep (>10°) upper slope. From there, debris flows and turbidity currents transported the debris further down to the adjacent continental rise (Pudsey and Camerlenghi, 1998). At Site 1095, these laminated sediments are interbedded with massive or bioturbated fine-grained sedimentary units (shown in black in column C of Fig. 3[5]). The bioturbated facies presumably was generated during interglacial periods (Pudsey, 2002b), when seasonally open ocean conditions favored biological productivity in the surface waters. As a consequence, the enhanced flux of organic matter to the seafloor enabled the bioturbation of the sediments by benthic organisms. Massive sediments are characterized by the absence of primary sedimentary structures, except for diffuse grading. Pudsey (2002b) proposed that the massive facies essentially is associated with bioturbation of condensed fine-grained hemipelagic sediments. Like the bioturbated facies, the massive facies presumably was deposited during interglacials, i.e., when grounded ice was confined to the inner shelf areas.

According to the depositional model outlined in the previous paragraph, the alternation of the laminated facies with the bioturbated/massive facies at Site 1095

[5] Depth ranges for bioturbated zones are those described by the Shipboard Scientific Party (1999b).

could simply represent alternating glacial and interglacial conditions, respectively. In this scheme, a glacial cycle begins at the base of a laminated unit and ends at the top of the overlying bioturbated/massive unit. If so, the alternations of laminated and bioturbated/massive facies at Site 1095 suggest that there were at least 24 cycles of APIS advance/retreat on the outer continental shelf during the Late Miocene and Early Pliocene (see column C in Fig. 3). Six grounding events should have occurred during the time interval spanned by the *T. inura* (subzone a) biozone, six grounding events during the time period of the *T. oestrupii*/*N. reinholdii* biozone, and twelve grounding events during the time interval defined by the *A. ingens* var. *ovalis* biozone (Table 1).

3.2.2. Grounding-events inferred from clay mineralogical cycles

Hillenbrand and Ehrmann (2002) recognized two distinct clay mineral assemblages at Site 1095. One assemblage is characterized by >20% smectite and <40% chlorite, and a second assemblage is characterized by <20% smectite and >40% chlorite. The authors' interpretation of these clay mineral fluctuations is based on the modern clay mineral provenance and oceanography of the region and clay mineral variations associated with Late Quaternary glacial cycles. Clay mineral analyses of surface sediments on the Antarctic Peninsula's Pacific margin show that a clay mineral assemblage enriched in smectite characterizes modern sediments on the rise south of 63° S. Hillenbrand and Ehrmann (2002) suggested that during the present (and earlier) interglacial period smectite-rich detritus from the shelf to the northeast of Drift 7 (around the South Shetland Islands) is transported oceanwards across the shelf edge by icebergs and tidal and wind driven currents and entrained by hemipelagic settling into an anticlockwise flowing bottom current on the rise. The contour current transports the smectite-rich clay to the southwest and deposits it on Drift 7 together with detritus supplied from the adjacent shelf.

In contrast to the modern sediments on Drift 7, those from the adjacent shelf are enriched in chlorite and thus resemble clay mineral assemblages deposited on the continental rise during Late Quaternary glacial periods (Pudsey, 2002b; Hillenbrand and Ehrmann, 2002; Lucchi et al., 2002). Hillenbrand and Ehrmann (2002) concluded that during glacial periods grounded ice masses advanced across the shelf adjacent to Drift 7 and thereby eroded the underlying sediments. The ice masses released vast amounts of chlorite-enriched detritus at the shelf break and gravitational down-slope processes transported this material down to the continental rise, where the chlorite-rich detritus diluted the smectite-rich clay delivered from the northeast via the bottom current. Consequently, the authors considered the second clay mineral assemblage at Site 1095 (<20% smectite and >40% chlorite) to be deposited during ice sheet grounding events.

Forty-five clay mineral analyses were performed by Hillenbrand and Ehrmann (2002) on the sedimentary sequence at Site 1095 that corresponds to seismostratigraphic Package-3 on the shelf. Sample depths were selected based on the preliminary shipboard descriptions of bioturbated/massive versus laminated sediments. Thirty samples were taken from laminated sediments and fifteen samples were taken from bioturbated/massive sediments. In Fig. 3, we linearly interpolated the clay mineral composition between the sample depths. We define a full interglacial–glacial cycle to begin with a sample exhibiting a low smectite (<20%) and high chlorite content (>40%) and to end with a sample exhibiting a high smectite (>20%) and low chlorite content (<40%). Accordingly, the clay mineral alternations at Site 1095 suggest that there were at least fourteen cycles of APIS advance/retreat on the outer continental shelf during the Late Miocene and Early Pliocene (see column D in Fig. 3). Based on this evidence, there were at least two grounding events during the time of the *T. inura* biozone, at least two grounding events occurred during the time period, which is spanned by the *T. oestrupii*/*N. reinholdii* biozone, and at least ten grounding events took place during the time interval corresponding to the *A. ingens* var. *ovalis* biozone (Table 1).

4. Discussion

4.1. The relation of APIS grounding events documented on the shelf to sedimentary cycles on the continental rise

The relatively high number of sedimentary cycles on the continental rise within three of the four biozones we considered (*A. ingens* var. *ovalis*[6], *N. reinholdii*, and *T. oestrupii*) is consistent with the view that this deeper

[6] On the continental shelf, Site 1097 did not reach the bottom of the *A. ingens* biozone. According to Bart and Anderson (1995) only three Package-3 grounding events occurred within the time interval represented by Package-3strata below the bottom-hole depth at Site 1097. These grounding events are represented by Unconformities 3.15, 3.16 and 3.18. So, even if these three additional grounding events occurred during *A. ingens* biozone, the maximum number of grounding events that could be predicted from the seismic record on the shelf would be five which is still an order of magnitude less than the 12 laminated–bioturbated or 10 clay mineral cycles within the coeval biozone on the continental rise.

water setting contains a more complete record of APIS grounding events than that preserved on the outer continental shelf. Other raw log measurements (e.g., reflectance, natural gamma ray and magnetic susceptibility) also exhibited a relatively high number of cycles (Lauer-Leredde et al., 2002). On the other hand, some of the massive sedimentary units interbedded with laminated sections at Site 1095 may not represent interglacial deposits but homogenized deposits resulting from small-scale slumps on the flanks of Drift 7 during glacial periods. If some massive units were generated by slumping, then the continental-rise sedimentology would incorrectly indicate a higher-than-actual number of glacial–interglacial cycles. Indeed, Pudsey (2002b) reported diffuse grading from some massive units, and high-resolution multibeam images show that drifts in the study area are marked by numerous steps interpreted to be scars left by slope slides or failures (e.g., Amblas et al., 2006).

In the case of the fourth biozone we considered (*T. inura* subzone a), the number of cycles of sedimentary structures on the continental rise is actually lower than the number of grounding events on the shelf (Table 1). This unexpected result opens the possibility that some sedimentary cycles on the continental rise were amalgamated. For example, within the depth interval corresponding to *T. inura* (subzone a) on the continental rise, the laminated sections of the cycles are thin relative to the thickness of the overlying bioturbated/massive sections. Perhaps a relatively thick bioturbated/massive section corresponds to more than one interglacial period, with intense bioturbation during a subsequent interglacial having destroyed the lamination of a thin sequence deposited during the previous glacial period.

The resolution of the clay mineral data set provided for Site 1095 obviously is too low to evaluate whether fluctuations in smectite–chlorite ratios record APIS grounding events interpreted from the outer continental shelf seismostratigraphy or deduced from laminated and bioturbated/massive structures. For example, within *T. inura* (subzone a) on the continental rise, at least sixteen optimally positioned samples would be needed to resolve a minimum of eight grounding events interpreted from the seismic profiles from the outer continental shelf. Given that only six clay mineral analyses were conducted within the *T. inura* (subzone a) biozone, it would be possible to resolve a maximum of three clay mineralogy cycles. The number of clay mineral analyses is also too low to resolve the global climatic cycles expected for the Late Miocene and Early Pliocene (40 ka period according to Hodell et al., 2001; cf. Hillenbrand and Ehrmann, 2002) or the same cycles indicated by the sedimentary structures at Site 1095. For example, of the twenty-four cycles visible in the sedimentary structures associated with the Upper Miocene and Lower Pliocene, only eight cycles were sufficiently sampled for clay mineral analysis.

Regardless of the under-sampling problem for the clay mineralogy outlined above, the two proxies should be in agreement if cycles of sedimentary structures and clay mineralogical cycles both record the same phenomena. In other words, chlorite-rich clay mineral assemblages should dominate laminated sediments whereas smectite-rich clay mineral assemblages should dominate bioturbated/massive sediments, as was reported for the Late Quaternary. Indeed, of the fifteen samples taken from bioturbated/massive units, fourteen are enriched in smectite which represents a 93% agreement between these two different proxies (Fig. 3). However, of the thirty samples from laminated units, only eighteen (i.e. 60%) show the expected chlorite enrichment whereas twelve exhibit smectite enrichment expected for interglacial sediments. This contradiction opens the possibility that some laminated sediments are actually contourites accumulated during interglacials. If so, the contourite sedimentation would have been sufficiently high or the degree of bioturbation relatively low during at least a part of an interglacial period such that the contourite laminations were buried and preserved. This hypothesis is corroborated by relatively high diatom concentrations reported from some laminated units within the Upper Miocene and Lower Pliocene sequence at Site 1095 (Pudsey, 2002b) pointing to an interglacial origin of these laminated units. The lack of bioturbation in those sediments may be explained by a relatively low supply of organic matter to the seafloor caused by relatively low biological production in the surface waters in response to a relatively short open ocean season during a moderate interglacial period. If this scenario is correct, sedimentological criteria (e.g., graded versus non-graded bedding) might also allow laminations caused by interglacial contourite deposition to be objectively distinguished from laminations associated with glacial turbidites. Another possibility is that the clay mineral provinces exposed in the source areas along the Antarctic Peninsula may have changed during the Late Miocene and Early Pliocene. For example, Hillenbrand and Ehrmann (2002) pointed out that the clay mineral assemblages deposited on Drift 7 during the Late Miocene were generally enriched in smectite, probably because of intensified glacial erosion of smectite-bearing rocks in the South Shetland Island area due to local uplift processes.

Drift sediments include a mixture of fine-grained turbidites, hemipelagites containing ice-rafted debris

(IRD) and muddy contourites. Interpreting the drift stratigraphy in terms of glacial history relies on the model-driven assumption that successive grounding events produced a similar stratigraphy. Particularly, those sediments deposited from down-slope turbidity currents are supposed to be linked to grounded ice advances across the adjacent shelf. However, there are several plausible reasons why this may not have been the case. Shifts from a line- to a point-sourced style of sedimentation would dramatically affect the style of sedimentation at down-slope locations. Likewise, shifts in the position of ice streams on the outer continental shelf during a single or successive APIS grounding events would produce a significant change in the point of sediment input to the drift. Slope failures unrelated to the APIS glacial cycles would also mask any otherwise inherent glacial signal (Pudsey, 2002b). Advance/retreat of the APIS restricted to the inner continental shelf probably would not produce the same drift sequence as that associated with a grounding event affecting the outer continental shelf. The presence of ice rafted debris (IRD) in drift sediments indicates only that glaciers reached sea level and distributed sediment by icebergs (Cowan, 2002). Therefore, IRD deposited on the continental rise may have been delivered by icebergs drifting in the circumpolar current from the other side of the continent thus partially recording glacial history from a distant region (Cooke and Hays, 1982; Wise et al., 1991; Anderson, 1999). Other sedimentary characteristics of the drift sediments may be related to long-term fluctuations in seasonal sea-ice formation, variations in the intensity, location and width of deep-water currents, etc., which may or may not have been directly related to the migration of grounded ice on the adjacent continental shelf. For example, Sagnotti et al. (2001) showed that coercivity minima observed in fine-grained Late Quaternary sediments from the continental rise of the western Antarctic Peninsula reflect changes in the input of detrital organic matter controlled by sea-ice extent (as opposed to grounded-ice extent) which they linked to the major rapid cooling events of the northern Atlantic (Heinrich layers).

Unfortunately, with the existing poor chronostratigraphic resolution for the continental shelf strata (Iwai and Winter, 2002), it is not yet possible to demonstrate that discrete cycles on the drift were genetically produced by discrete APIS grounding events on the continental shelf. For example, it is not possible to determine if grounding event 3.14 on the continental shelf comes from the top, middle, or bottom of the *A. ingens* var. *ovalis* biozone. Thus, grounding event 3.14 could conceivably be associated with any of the twelve bioturbation cycles (13 thru 24 on Fig. 3) within the coeval section on the drift at Site 1095. Although the genetic links between cyclic deposition on the rise and dynamics of the APIS documented on the shelf cannot be established for the Late Miocene and Early Pliocene, several model-based sedimentologic investigations support the theory of direct linkages (e.g., Pudsey and Camerlenghi, 1998; Pudsey, 2002b). Hepp et al. (2006) conducted a detailed evaluation of physical and geochemical properties (e.g., color reflectance, X-ray fluorescence, magnetic susceptibility, bulk density, natural gamma, etc.) for three core segments from Site 1095B (3H, 5H, and 10H). From these bases, they defined two boundary types (sharp interglacial-to-glacial transitions and diffuse glacial-to-interglacial transitions) that they interpret within the context of a five-stage model relating grounding events to drift deposition. At Site 1101 (to the northeast of the Site 1095, see Fig. 1), Cowan (2002) showed that many drift cycles exhibited an increased IRD abundance from laminated sediments up-section to peak values in an overlying bioturbated muds. The increased mass accumulation rate of IRD within bioturbated muds probably was due to rapid disintegration of ice streams and release of icebergs from the continental shelf (Cowan, 2002). Gruetzner et al. (2003) used a similar reasoning to interpret East Antarctic Ice Sheet glacial dynamics from lithofacies and IRD-abundance changes at Site 1165 on the continental rise adjacent to Prydz Bay, East Antarctica.

The total number of cycles of sedimentary structures at Site 1095 (Fig. 3) is much lower than the number of δ^{18}O cycles evident in coeval section at Site 982 (Hodell et al., 2001). The marked mismatch in the overall number of cycles (24 versus 56[7]) suggest that the primary control on continental-rise sedimentology at Site 1095 during this part of the Late Neogene may not have been directly linked to 40-ky orbital tilt cycles of global-scale ice-volume and/or temperature changes as recorded on deep-sea δ^{18}O data. Since the continental-rise sedimentation rates at Site 1095 varied from ~20 to 110 m/My between interglacial to glacial periods (Shipboard Scientific Party, 1999b), detailed analyses are needed to precisely access how well drift cycles match Milankovich oribital periodicities (Lauer-Leredde et al., 2002). Several recent studies have demonstrated

[7] Oxygen isotope stages are not officially numbered for section of this age. Our estimate of 56 cycles is based on our visual inspection of the Site 982 δ^{18}O record (Hodell et al., 2001). The rough estimate is based on an approximate minimum shift of 0.25 from heavy to light δ^{18}O values.

that some Antarctic drift sections exhibit orbital cyclicity and inferred that these cycles probably were in turn associated with Antarctic Ice Sheet volume and grounding-zone fluctuations (e.g., Cowan, 2002; Gruetzner et al., 2003; Iorio et al., 2004; Hepp et al., 2006). That some Antarctic drift sections contain orbital cycles neither requires nor precludes that these drift cycles were indeed related to ice-volume and/or grounding zone migrations on the adjacent sector of the continent. In other words, the challenge remains to unambiguously demonstrate that the cyclicity noted on drifts is a manifestation of ice-volume and grounding-zone fluctuations on the continent. Stated differently, the overriding question as to whether Antarctic Ice Sheet grounding-zone fluctuations and ice-volume fluctuations were controlled by orbital insolation cycles as opposed to autocyclic processes remains to be answered.

5. Conclusion

During the Late Neogene, sedimentary cycles on the Antarctic Peninsula's continental rise at Site 1095 are more numerous than the number of grounding events noted by Bart et al. (2005) on the adjacent continental shelf for three of four biozones we considered. This result suggests that the drifts on the continental rise may contain a high-resolution record of APIS glacial history. Because of the low chronostratigraphic resolution on the continental shelf, it is not possible to demonstrate direct genetic linkages between grounding events and sedimentary cycles inferred from the continental-rise record. This inability to establish direct correlations between the shelf and rise is problematic because other explanations unrelated to ice-sheet grounding events (e.g., changes in sea-ice extent, variations in the intensity of deep-sea currents, changes in IRD distribution pattern, etc.) cannot be conclusively excluded as the possible cause of the observed sedimentary cyclicity on the continental rise. It is also apparent that the two sedimentological proxies we considered in this study do not always provide a consistent picture of APIS glacial history. If problems with the temporal resolution of sampling and contradictions between proxy evidence can be adequately addressed in the future, the continental-rise record may ultimately solve the larger problem of a more accurate reconstruction of Antarctic Ice Sheet fluctuations and the correlation of grounding events with sea-level and climatic changes. Our study underlines the importance of studying both the proximal, but incomplete record of grounding events on the Antarctic shelf and the distal, but more complete sedimentary record on the Antarctic continental rise.

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