Direct constraints on Antarctic Peninsula Ice Sheet grounding events between 5.12 and 7.94 Ma

Philip J. Bart, Dave Egan, and Sophie A. Warny[1]

Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana, USA

Received 19 October 2004; revised 12 May 2005; accepted 10 June 2005; published 1 November 2005.

[1] How has the Antarctic Ice Sheet responded to or influenced global climate change? This simple question has been difficult to address because the long-term records of the ice sheet's fluctuations are poorly constrained with geologic data from Antarctica. Thus studies to date have not convincingly established how specific Antarctic Ice Sheet events correlate with climatic, eustatic, or other phenomena known from low-latitude and deep-sea records. This study focused on documenting the direct record of ice sheet advance and retreat to the Antarctic Peninsula's shelf edge. On the peninsula's outer shelf, seismic reflectors interpreted to be subglacial unconformities were correlated with published results from Ocean Drilling Program Leg 178. Lithologic and chronologic control at two drill sites provided ground truth for the seismic interpretation and the timing of the Antarctic Peninsula Ice Sheet grounding events. This synthesis showed that grounded ice advanced to the shelf edge on at least 12 occasions between 5.12 and 7.94 Ma.

Citation: Bart, P. J., D. Egan, and S. A. Warny (2005), Direct constraints on Antarctic Peninsula Ice Sheet grounding events between 5.12 and 7.94 Ma, *J. Geophys. Res.*, *110*, F04008, doi:10.1029/2004JF000254.

1. Introduction

[2] Numerous lines of geologic, geophysical, and geochemical evidence show that the Antarctic Ice Sheet (AIS) has not been static. Unfortunately, details about the past fluctuations are extremely difficult to reconstruct with direct evidence from Antarctica because outcrops on the continent have a patchy distribution [e.g., *Denton et al.*, 1991; *Marchant et al.*, 1993]. On the continental shelves, where stratigraphic superposition is reasonably constrained, lithologic and chronologic ground truth is generally lacking [e.g., *Barrett and McKelvey*, 1986; *Barrett et al.*, 1989; *Hayes and Frakes*, 1975; *Barron et al.*, 1991; *Cooper et al.*, 2004]. It is fundamental to understand and test which mechanisms drive ice sheet fluctuations within the context of climate or other phenomena known from deep-sea and low-latitude records. To do so, direct records of cryosphere dynamics must be established. Moreover, since the AIS consists of three distinctly different glacial systems (Figure 1, inset), ice sheet fluctuations from each sector of Antarctica have to be analyzed separately [*Denton et al.*, 1991; *Bart and Anderson*, 2000]. This is because dynamics in one sector may not be representative of fluctuations occurring elsewhere on the continent.

[3] With these considerations in mind, recent drilling during Ocean Drilling Program (ODP) Leg 178 to the Antarctic Peninsula (Figure 1) provides an opportunity to directly constrain Antarctic Peninsula Ice Sheet (APIS) fluctuations. Recovery of glaciogenic sediments and age control from the outer continental shelf confirm that glacial conditions affected the peninsula since at least the late Miocene [*Barker and Camerlenghi*, 2002]. The specific purpose of our study is to critically evaluate an existing seismic-based interpretation of the sequence of APIS grounding events proposed by *Bart and Anderson* [1995]. This investigation incorporates published lithologic and chronologic ground truth from ODP Leg 178 and new contour mapping from a regional grid of single-channel seismic data acquired in 2002. Three fundamental questions concerning the APIS are addressed: (1) Did grounded ice advance to the Pacific margin shelf edge? (2) If so, what was the style of these glaciations? (3) What was the timing of the individual grounding events?

2. Background

2.1. Bathymetric Features, Near-Surface Sedimentology, and Relationships to Stratal Patterns

[4] Antarctica's continental shelves were overdeepened and foredeepened by repeated advance and retreat of grounded ice. On the Antarctic Peninsula, ice streams carved a series of foredeepened troughs and banks [*Vanney and Johnson*, 1974; *Rebesco et al.*, 1998]. Marguerite Trough, the largest trough draining the mainland peninsula, is ~200 km wide with ~200 m of relief with respect to adjacent banks (Figure 1). Smaller troughs in the region have widths ranging from 40 to 130 km with ~200 m relief. Recent multibeam surveys revealed seafloor lineations showing that grounded ice drained the mainland and extended to the shelf edge [*Canals et al.*, 2000; *Heroy and Anderson*, 2003; *Dowdeswell et al.*, 2004]. The lineations were carved into terrigenous sediments that presumably were deposited and remolded as grounded ice

[1]Also at Museum of Natural Science, Louisiana State University, Baton Rouge, Louisiana, USA.

0148-0227/05/2004JF000254$09.00

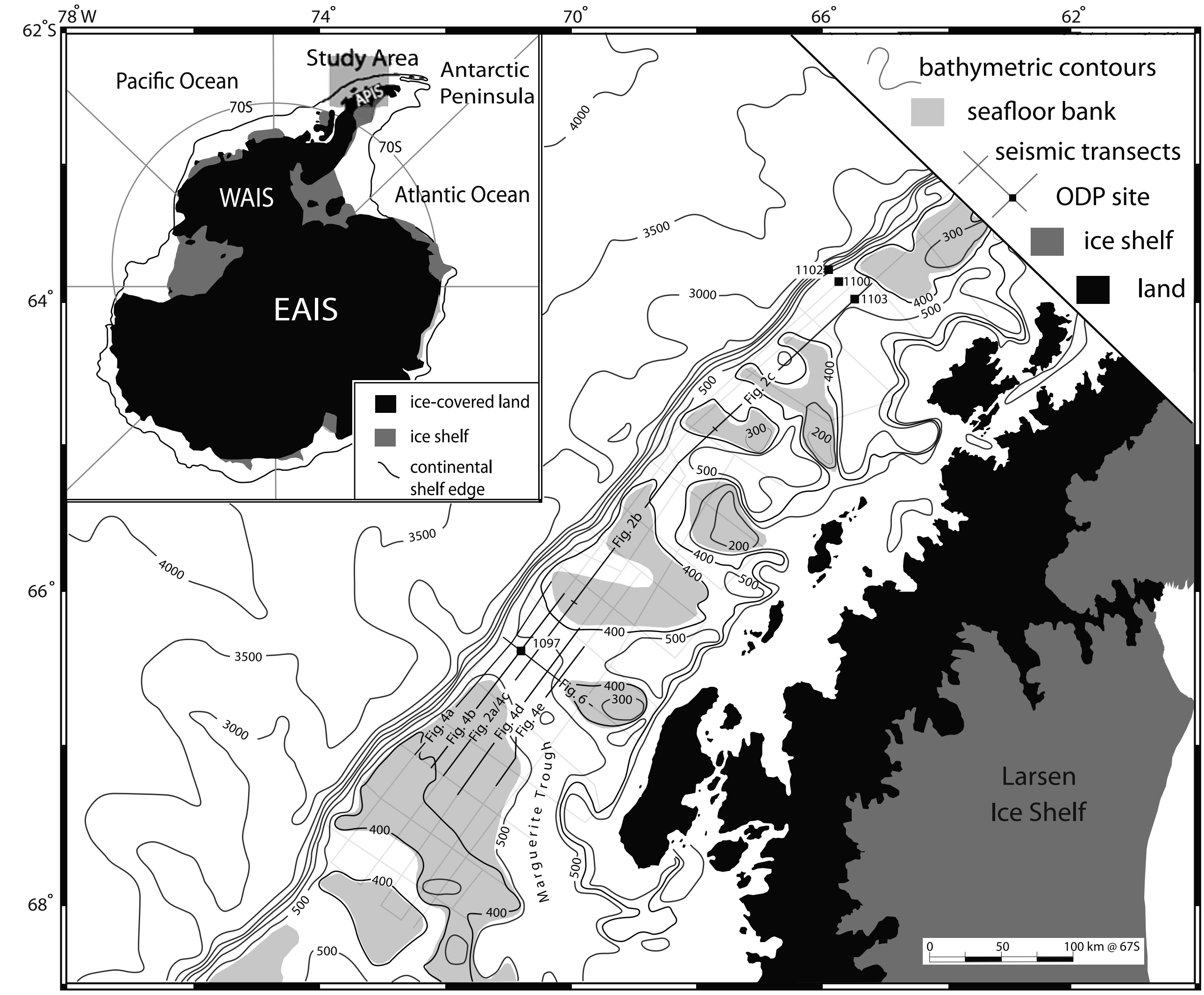

Figure 1. Antarctic Peninsula bathymetry contours in meters from *Rebesco et al.* [1998] and seismic grids (light gray lines). Light shaded pattern shows the location of seafloor banks. Unshaded areas correspond to locations of ice streams during the last advance of grounded ice to the shelf edge. The inset shows the position of the Antarctic Peninsula with respect to the entire continent. EAIS, East Antarctic Ice Sheet; WAIS, West Antarctic Ice Sheet; APIS, Antarctic Peninsula Ice Sheet.

advanced across the shelf. These sediments were capped by thin diatomaceous muds that accumulated in the time since the ice sheet retreated from the continental shelf [*Kennedy and Anderson*, 1989; *Pope and Anderson*, 1992; *Pudsey et al.*, 1994]. This interpretation has been well supported by seismic, swath bathymetry and piston core investigations of late Quaternary sediments on the Antarctic shelves [*Anderson*, 1972; *Kellogg et al.*, 1979; *Anderson et al.*, 1980; *Elverhøi*, 1981; *Domack*, 1982; *Anderson et al.*, 1984; *Kennedy and Anderson*, 1989; *Anderson et al.*, 1991; *Pope and Anderson*, 1992; *Vanneste and Larter*, 1995; *Larter and Vanneste*, 1995; *Licht et al.*, 1996; *Shipp et al.*, 1999; *Domack et al.*, 1999; *Bart et al.*, 2000; *Howat and Domack*, 2003].

[5] In the subsurface, crosscutting relationships within a basinward thickening wedge suggested a pre-Quaternary history of glaciation of the peninsula's outer shelf [*Larter and Barker*, 1989; *Anderson et al.*, 1991; *Bart and Anderson*, 1995; *Larter and Vanneste*, 1995]. In these studies, seismic reflectors exhibiting top set geometry, truncation of underlying horizons and regional extent were interpreted to be unconformity surfaces eroded by grounded ice. Similar stratal patterns on other Antarctic continental shelves were also inferred to result from advance and retreat of grounded ice sheet [*Hambrey et al.*, 1991; *Bartek et al.*, 1991; *Cooper et al.*, 1991; *Hambrey et al.*, 1991; *Anderson and Bartek*, 1992; *Cooper et al.*, 1993; *Hambrey*, 1993; *Larter and Cunningham*, 1993; *Moons et al.*, 1992; *Pudsey et al.*, 1994; *Eittreim et al.*, 1995; *Brancolini et al.*, 1995; *De Santis et al.*, 1995; *Antarctic Offshore Acoustic Stratigraphic Project*, 1995].

2.2. Antarctic Peninsula's Glacial History From the Perspective of the Outer Continental Shelf

[6] On the Antarctic Peninsula's Pacific margin, the shelf wedge has been subdivided into four seismic packages [*Larter and Barker*, 1989; *Bart and Anderson*, 1995]. *Bart and Anderson* [1995] referred to the upper three sections as

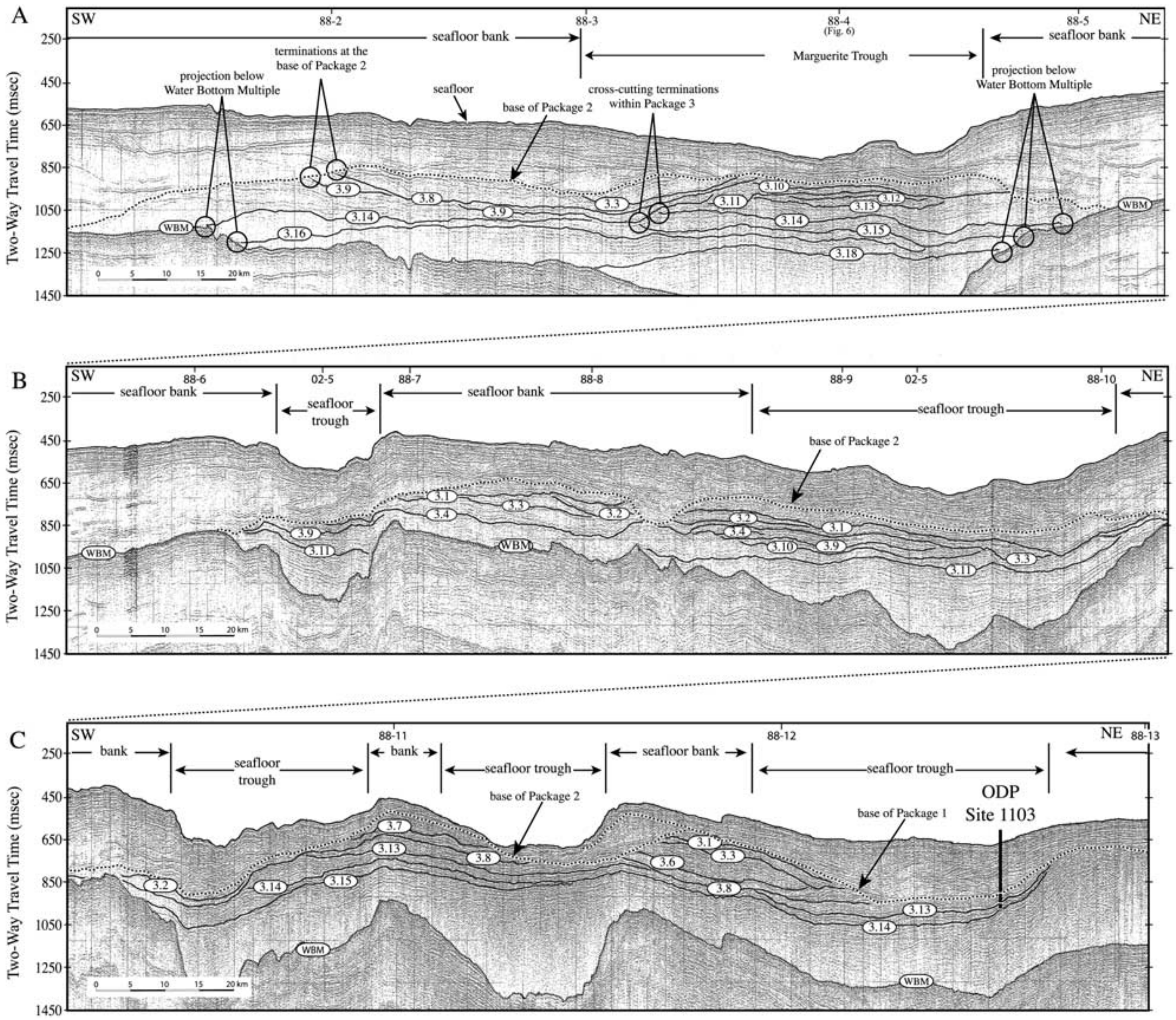

Figure 2. Southwest-northeast (strike-oriented) regional seismic profile NBP02-03 on the outer continental shelf (see Figure 1 for location). (a) South segment, (b) central segment, and (c) north segment. The top of package 3 is shown as a heavy dotted line. The youngest package 3 unconformity is 3.1, and the oldest is 3.18. ODP Site 1103 is located at the northeastern part of the study area (i.e., bottom segment of seismic profile).

packages 1, 2, and 3. The consensus view is that packages 1 and 2 were associated with multiple grounded events on the outer continental shelf [*Larter and Barker*, 1989; *Larter and Cunningham*, 1993; *Bart and Anderson*, 1995; *Larter and Vanneste*, 1995; *Vanneste and Larter*, 1995]. However, the glacial character of package 3 is debated. *Larter and Barker* [1989] and *Larter et al.* [1997] used multichannel seismic data to propose that deposition of package 3 was not associated with glacial conditions. In contrast, *Bart and Anderson* [1995] used higher-resolution single-channel seismic to propose that 18 grounding events occurred during package 3 time.

3. Methods

[7] In this study, two tests were performed to evaluate the glacial history interpretation for package 3. The first test involved contour mapping of seismic reflectors interpreted as glacial unconformities to determine if these horizons exhibit glacial trough topography. The seismic grids were acquired with either one or two 100 in^3 water guns or a 100 in^3 generator-injector air gun. Subsurface contour maps were constructed using three single-channel seismic grids (PD88, PD90, and a new grid, NBP02). The new seismic grid has four strike-oriented transects, which should permit contour mapping of the seismic reflectors interpreted by *Bart and Anderson* [1995] to be glacial unconformities. Elevations of seismic reflectors were measured in two-way travel time (TWTT) and contoured at a 20 ms contour interval.

[8] The second test involved seismic correlation with published lithologic control at ODP Leg 178 sites on the continental shelf to determine if units bound by seismic reflectors contain subglacial till. Sites 1097 and 1103 are the

Table 1. Distribution of Package 3 Unconformities on the Outer Continental Shelf Segments (South, Central, and North)[a]

South Segment (16)	Central Segment (6)	North Segment (14)
3.1	3.1	3.1
3.2[b]		3.2
3.3[c] (Figure 3)	3.3[c] (Figure 3)	3.3[c] (Figure 3)
3.4	3.4	3.4
3.5 (Figure 5a)		3.5
		3.6
		3.7
3.8		3.8
3.9[b,c] (Figure 5b)	3.9	3.9
3.10	3.10	3.10
3.11[b,c] (Figure 5c)	3.11	3.11
3.12[c]		
3.13[b,c] (Figure 5d)		3.13[c]
3.14[c]		3.14[c]
3.15		3.15[c]
3.16[c] (Figure 5e)		
3.17		
3.18		

[a]Values in parentheses are number of unconformities observed for that segment of the study area.
[b]Unconformity numbers for which the time structure contour maps are presented in this study (see Figures 3 and 5a–5e).
[c]Places where the units are sampled (at Site 1097 in the south segment and at Site 1103 in the north segment).

only two shelf sites that were drilled deep enough to penetrate package 3. To project the seismic reflectors to ground truth at sites 1097 and 1103, the TWTT elevations of seismic reflectors were measured and converted to depth. The *Moerz et al.* [2002] TWTT-depth chart for Site 1097 was not used because the electric log velocity measurements were unreliable. Instead, we created a TWTT-depth conversion table using the 42 measurements of *P* wave velocity from a Hamilton-Frame sensor pair [*Shipboard Scientific Party*, 1999]. Our linear interpolation of TWTT-depth pairs for Site 1097 is available in the auxiliary material[1]. At Site 1103, we used the *Tinivella et al.* [2002] velocity estimates to convert the TWTTs of package 3 seismic reflectors to depth.

[9] *Eyles et al.* [2001] presented lithologic descriptions and interpretations of depositional environments for Site 1097. Their interpretations of Site 1097 were used in this study. For Site 1103, the *Shipboard Scientific Party* [1999] presented detailed descriptions of lithofacies, but they did not interpret the depositional environments. We used the written descriptions presented by the *Shipboard Scientific Party* [1999] to interpret the depositional environments at Site 1103. Our primary intention was to provide a preliminary evaluation of how lithofacies and depositional environments changed with respect to the position of seismic reflectors. The core recovery at Site 1103 was slightly higher than at Site 1097, but a detailed evaluation of Site 1103 sedimentology was beyond the scope of this study. We acknowledge that a more detailed analysis of the Site 1103 sedimentology is needed to check our preliminary interpretations.

[10] Seismic reflectors were correlated with the diatom biozones described by *Winter and Iwai* [2002] to constrain the timing of grounding events. The diatom biozone ages for the peninsula [*Iwai and Winter*, 2002] were deemed more meaningful than ages for the Indian Ocean sector [*Harwood and Maruyama*, 1992]. The *Iwai and Winter* [2002] biozones ages were reported with respect to the *Cande and Kent* [1995] timescale.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/jf/2004JF000254.

4. Results

4.1. Stratal Relationships and Distribution of Package 3 Seismic Reflectors

[11] Correlations with the new seismic grid show that package 3 reflectors have a similar 2-D topography to that previously noted by *Bart and Anderson* [1995]. Crosscutting is so common that no individual unconformity correlates across the entire study area. In some places, unconformities at the base of either package 1 or 2 deeply erode into package 3. For example, the basal unconformity of package 2 truncates unconformity 3.9 near the left-hand side of profile NBP02-03 (Figure 2a). Elsewhere, younger package 3 unconformities truncate older package 3 unconformities. For example, unconformity 3.9 truncates unconformities 3.14 and 3.15 (middle part of Figure 2a). Regional seismic correlation is not possible because package 3 projects below the water bottom multiple (WBM) in two broad areas on the outer continental shelf (Figure 2).

[12] The crosscutting relationships and the projections of package 3 strata below the WBM define south, central and north study area segments. The limits of these three segments correspond to the threefold subdivision of seismic profile NBP02-03 in Figure 2. Within any one segment, stratigraphic superposition is well constrained. In the south segment, there are 16 individual seismic reflectors. In the central and north segments, there are 6 and 14 individual reflectors respectively (Table 1). The areal dimensions of package 3 seismic reflectors are as small as 600 km^2 and as large as 5100 km^2. The average map dimension for package 3 reflectors is $\sim$2000 km^2. In the south segment, unconformity 3.3 covers an area of $\sim$1250 km^2 whereas in the central and north segments, the areas are $\sim$2500 km^2 and $\sim$1000 km^2 respectively (Figure 3). In most cases, trough bank topography is not evident (Figures 4, 5a, 5c, and 5e). In other cases, features that might represent trough remnants (Figures 3, 5b, and 5d) do not appear to exhibit cross-shelf extents.

4.2. Seismic Correlation With Ground Truth at ODP Site 1097

[13] According to our TWTT-depth conversions (Table 2), ODP Site 1097 penetrates only 6 of the 16 package 3 reflectors in the south segment of the study area (Figures 4b and 6). At Site 1097, package 3 corresponds to core segments 23R to 51R (Figure 6). For this depth interval, core recovery is 16.7%. All seven units at Site 1097 contain glaciogenic sediments (Figure 6). Five of the units (units 3.14, 3.13, 3.12, 3.11, and 3.10) contain sediments interpreted to be subglacial in origin [*Shipboard Scientific Party*, 1999; *Eyles et al.*, 2001].

[14] The chart on Figure 6 (right) shows our approximation of upcore lithologic change based on the recovery at Site 1097. This approximation assumes that no high-frequency changes in lithology correspond to the core gaps at Site 1097. In this scheme, units 3.14, 3.13 and 3.12 exhibit upcore transitions from glaciomarine sections at their bases

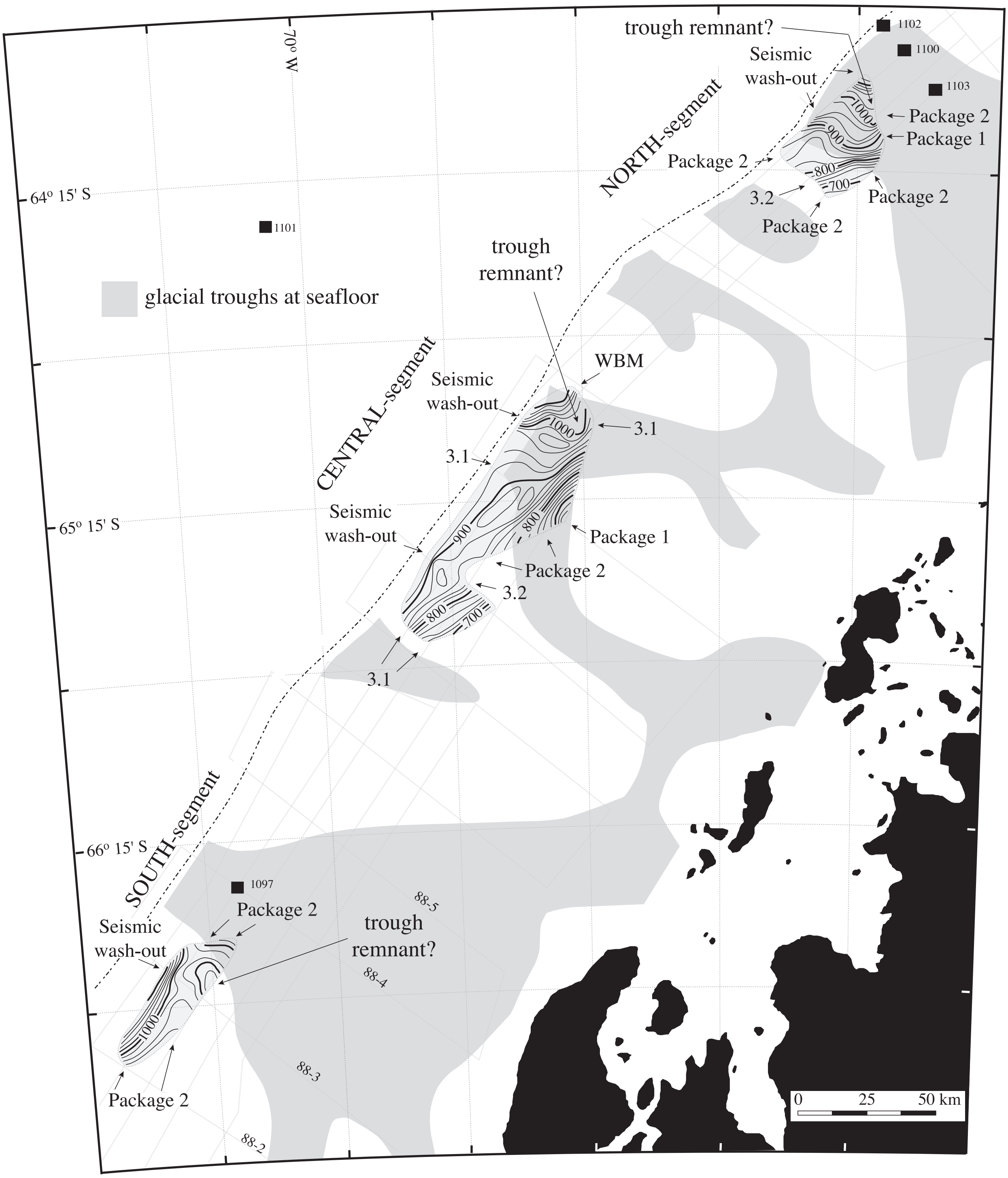

Figure 3. Distribution and topography of unconformity 3.3 contoured at a 20 ms (∼15 m) interval. The ODP sites (black squares) are shown. The limited extent of the unconformity is due to crosscutting stratal relationships. The numbers on the side of the map patches correspond to the overlying unconformity that truncates unconformity 3.3. The basinward limit (marked seismic washout) corresponds to the position of the paleoshelf edge. The position of the modern shelf edge is shown as a dashed line. Modern troughs are shown by the shaded areas.

to subglacial sections at their tops (Figure 6). The stratigraphy within these units corresponds to discrete progradational stacking patterns at Site 1097. For the uppermost part of unit 3.14, the upcore change from subglacial back to glaciomarine section indicates a retrogradational stacking pattern (Figure 6). The lithologic changes for the overlying four units (units 3.11, 3.10, 3.9 and 3.2) exhibit an overall aggradational stacking pattern (Figure 6). In units 3.11 and 3.10, subglacial sediments are present at the bases and tops of the units but, glaciomarine sediments are absent. In

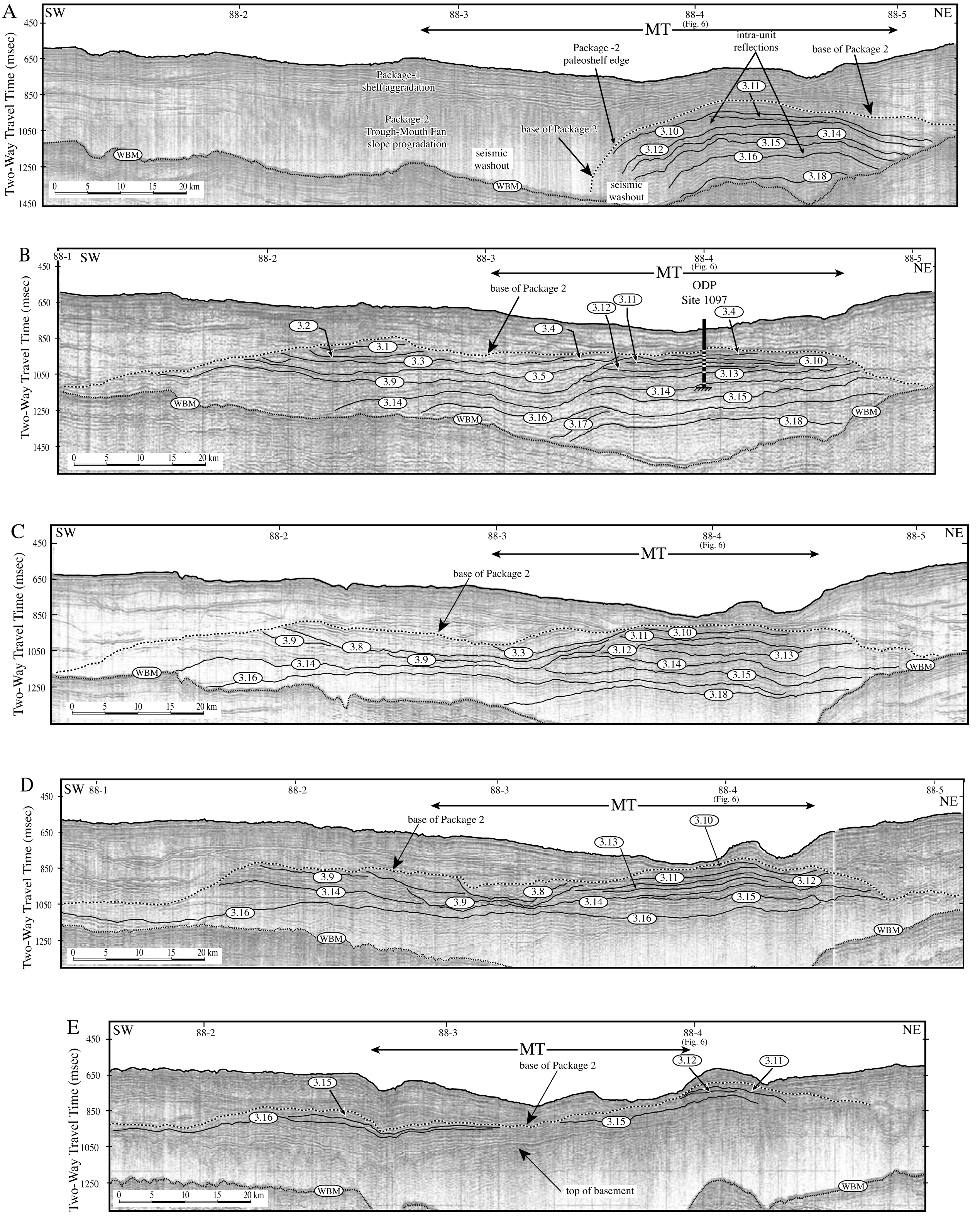

Figure 4. Segments of five regional strike-oriented seismic profiles on the outer continental shelf from the south segment part of the study area (see Figure 1 for locations). Individual reflectors exhibit complex crosscutting. Large-scale trough topography like that observed at the modern Marguerite Trough is not evident at any horizon. (a) Profile NBP02-5, the basinward-most transect. (b) Profile PD88-B, which crosses ODP Site 1097 at cross-line 88-4. Profiles (c) NBP02-3 and (d) NBP02-6, located on the middle shelf. Several older, intervening, and younger package 3 unconformities are not penetrated at Site 1097. (e) A thin layer of package 3 strata that overlies basement at profile NBP02-8, the landward-most transect.

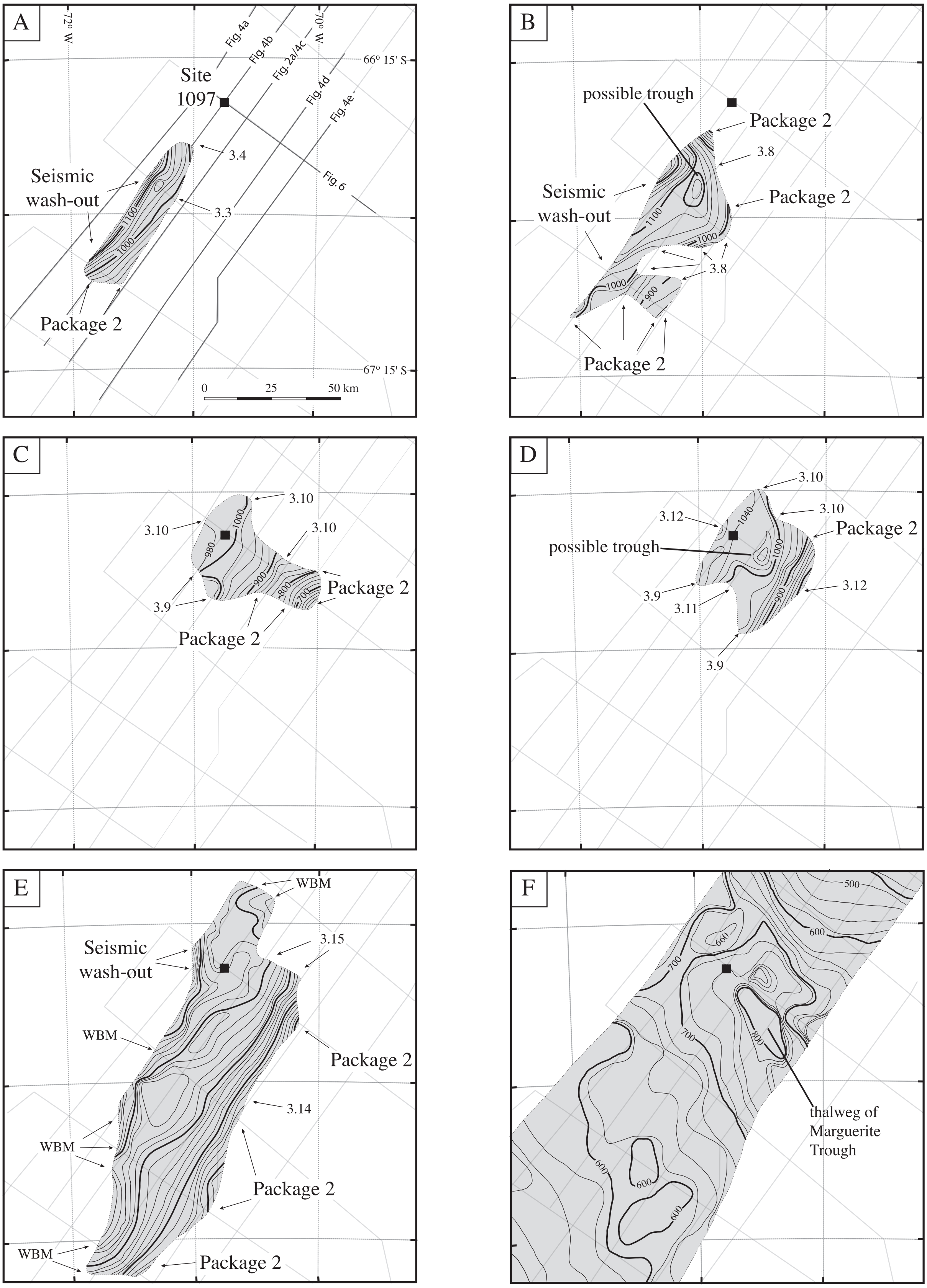

Figure 5. (a–e) Time structure contour maps of five package 3 seismic reflectors interpreted as glacial unconformities by *Bart and Anderson* [1995] and (f) the seafloor reflectors. Contours are in milliseconds below the sea surface. The numbers on the side of the map patches corresponds to the overlying seismic reflector that truncates the mapped horizon.

Table 2. Two-Way Travel Time of Seismic Reflectors at ODP Site 1097

Seismic Reflectors at Site 1097[a]	TWTT-Depth Conversion[b]		
	TWTT, ms bss	TWTT, ms bsf	Depth, mbsf
Seafloor	736	0	0
Base of package 2	906	170	178.08
Unconformity 3.4	934	198	203.26
Unconformity 3.10	952	216	223.93
Unconformity 3.11	975	239	252.18
Unconformity 3.12	995	259	273.16
Unconformity 3.13	1031	295	309.05
Unconformity 3.14	1095	359	377.11
"Bottom hole"	1150	414	436.6
Unconformity 3.15	1180	444	below BH
Unconformity 3.16	1227	491	below BH
Unconformity 3.18	1288	552	below BH

[a]This study.
[b]Two-way travel time (TWTT) reported in milliseconds below the sea surface (ms bss), milliseconds below the seafloor (ms bsf), and meters below seafloor (mbsf) calculated using our interpolation of discrete Hamilton-Frame velocity values reported by the *Shipboard Scientific Party* [1999]. BH, bottom hole. Using our linear interpolation of Hamilton-Frame velocity values reported by the *Shipboard Scientific Party* [1999].

units 3.9 and 3.2, glaciomarine sediments are present at the units' bases and tops, but subglacial sediments are absent (Figure 6). According to our TWTT-depth conversions (Figure 6), package 3 core segments correlate with four diatom biozones described by *Winter and Iwai* [2002]. These biozones are *Thalassiosira inura* (subzone a), *Thalassiosira oestrupii*, *Nitzschia reinholdii*, and *Actinocyclus ingens* var. *ovalis*.

4.3. Seismic Correlation to Ground Truth at ODP Site 1103

[15] According to our TWTT-depth conversions (Table 3), ODP Site 1103 penetrates only 2 of the 14 package 3 reflectors in the north segment of the study area (Figures 3 and 7). Table 3 shows TWTT-depth conversions derived from the *Moerz et al.* [2002] velocity model. For the reasons mentioned in section 3, this section focuses on depth conversions obtained from the *Tinivella et al.* [2002] velocity data (i.e., Table 3). At Site 1103, package 3 corresponds to core segments 27R to 38R (Figure 7). Core recovery is 36% for this section. Most of the sediment was described as glacial diamict with mudstones, siltstones, and claystones by the *Shipboard Scientific Party* [1999]. Some core segments contain laminations whereas others segments exhibit evidence of bioturbation or deformation. The caption for Figure 7 provides a detailed key for the lithologic descriptions. Diamict sediments at Site 1103 correlate with the tops of the three seismically defined units (Figure 7). Site 1103 samples only the middle and top of unit 3.14. In the middle of unit 3.14, laminated siltstones underlie diamict with dispersed clasts. At the top of unit 3.14, sandstones and mudstones contain deformational structures. In the overlying unit, laminated siltstones from near the base and middle of unit 3.13 underlie a clast-rich diamict near the unit's top. In the lower part of unit 3.12, diamict, laminated mudstone and sandstone underlie a bioturbated mud with fine laminations. Within the upper part of unit 3.12, diamicts contain variable amounts of clasts. Some laminated sediments near the top of the unit 3.12 exhibit evidence of deformation. The package 3 core segments correlate with the *Actinocyclus ingens* var. *ovalis* diatom biozone described by *Winter and Iwai* [2002].

5. Discussion

5.1. Glacial Unconformity Interpretation of Package 3 Seismic Reflectors

[16] Subsurface contour mapping (Figures 3 and 5) shows that dimensions of seismic reflectors are too small to map large-scale trough and bank topography evident at the seafloor. The along-strike topographic relief at the majority of the mapped horizons is too low to require a glacial trough interpretation as opposed to some other erosive process. Moreover, the map distributions are too widely separated and areal extents too limited to determine if any trough-like features extended across the shelf to the mainland peninsula. For example, similar outer shelf features may form by headward erosion at an upper slope canyon unconnected to a glacial trough on the outer continental shelf. Therefore the map topography of package 3 seismic reflectors does not conclusively require that these surfaces formed below grounded ice. Nonetheless, the patchy distribution of reflectors at an outer continental shelf location is important because it requires that glaciogenic sedimentation was interrupted by seafloor erosion on several occasions. Moreover, the downcutting at package 3 reflectors had to be sufficiently intense to deeply erode through thick glaciogenic sediments (>20 m) including clast-rich diamicts. Such large amounts of erosion make it unlikely that package 3 reflectors resulted from erosive processes involving winnowing by marine currents [*Dunbar et al.*, 1985]. For example, winnowing fines from 10 m of diamict containing 5% ice-rafted or subglacially transported clasts would produce a 0.5-m-thick armor. The lag produced from clast-rich sediments would have armored the seafloor against substantial erosion before the observed downcutting was accomplished. It is also unlikely that the area was subaerially exposed because there is no lithologic or seismic evidence of fluvial processes or soil development. The ubiquity of deep crosscutting and its association with glaciogenic sediments is most consistent with the view that these reflectors formed below grounded ice.

[17] The distribution of subglacial sediment throughout package 3 at ODP Site 1097 [*Eyles et al.*, 2001] clearly requires multiple grounding events (Figure 6). At Site 1103, we propose that clast-rich diamicts were deposited in either subglacial or grounding zone proximal settings (Figure 7). We infer that the deformational structures within siltstones and diamicts from units 3.14, 3.13 and 3.12 resulted from sediment mobilization below an overriding ice sheet. If these lines of reasoning are correct, then the lithologic evidence for Site 1103 also supports the view that grounded ice advanced to the shelf edge during the package 3 time frame. We acknowledge that a detailed sedimentologic analysis of Site 1103 is needed before our preliminary interpretations can be accepted.

5.2. Style of APIS Grounding Zone Advance and Retreat Across the Outer Continental Shelf

[18] If the arguments from section 5.1 are accepted, then seismic reflectors correspond to subglacial unconformities. Unfortunately, the poor recovery within seismically defined units at Site 1103 and the uncertainty of our preliminary

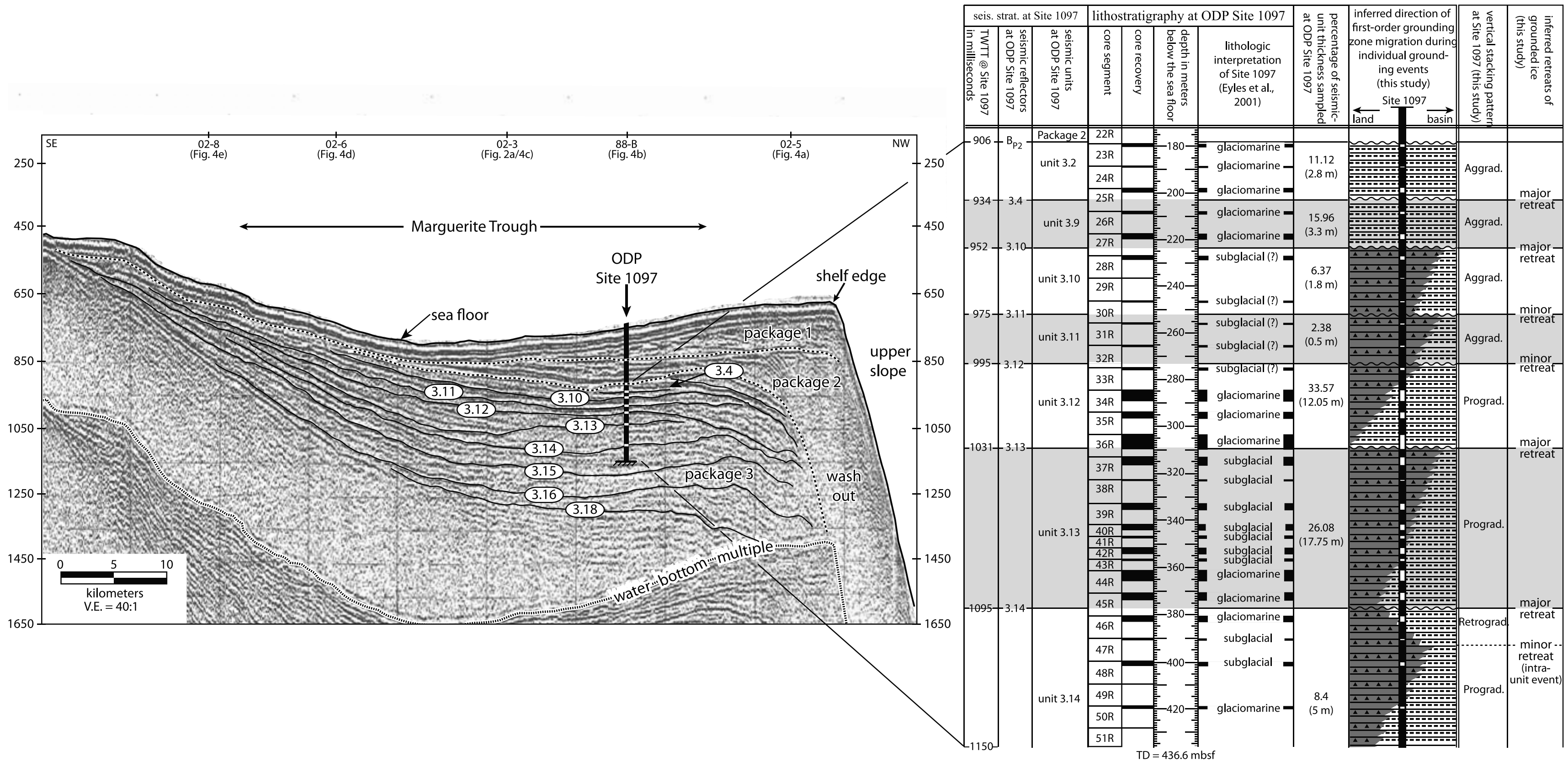

Figure 6. Dip-oriented seismic profile PD88-4 crosses ODP Site 1097 (see Figure 1 for location). The chart on the right-hand side shows the two-way travel time (TWTT) of the package 3 seismic reflectors in milliseconds below the sea surface. Lithologic interpretations are from *Eyles et al.* [2001]. Question marks indicate their uncertainty concerning the geologic interpretation. Upcore lithologic changes at the well bore were used to infer directions of grounding zone migration with respect to Site 1097. The dark shading with black triangles corresponds to subglacially deposited sediment. The lighter shading with dashes corresponds to glaciomarine sediment.

Table 3. Two-Way Travel Time and Depths of Seismic Reflectors at ODP Site 1103[a]

	TWTT-Depth Conversion					
	Tinivella et al. [2002] Velocity Model			*Moerz et al.* [2002] Velocity Model		
Seismic Reflectors at Site 1103[b]	TWTT, ms bss	TWTT, ms bsf	Depth, mbsf	TWTT, ms bss	TWTT, ms bsf	Depth, mbsf
Seafloor	670	0	0	670	0	0
Base package 1	900	230	240.28	900	230	256
Unconformity 3.13	950	280	309.83	950	280	327.8
Unconformity 3.14	975	305	344.61	975	305	below B.H.
Bottom hole	988	318	362.7	971	301.5	362.7

[a]Package 3 seismic reflectors at Site 1103, TWTT converted to depth using the *Tinivella et al.* [2002] velocity model and the TWTT converted to depth using the *Moerz et al.* [2002] velocity model are given. For each scheme, the elevation of the seismic reflectors are reported in milliseconds below the sea surface (ms bss), milliseconds below the seafloor (ms bsf), and meters below the seafloor (m bsf).
[b]This study.

interpretations make it difficult to evaluate how the lithofacies changes might relate to depositional style during individual grounding events. Because of this limitation, the following discussion pertains only to Site 1097. As mentioned in section 4, we assume that core recovery is sufficient to characterize how depositional environments changed. If this assumption is valid, all package 3 units at Site 1097 could have formed as prograding systems similar to that predicted by the till delta model [*Alley et al.*, 1989]. According to this model, proglacial sediment should underlie subglacial sediment and a subglacial unconformity should cap the sequence. The progradational stacking patterns for the lower part of unit 3.14, as well as for units 3.13 and 3.12, are consistent with this general view of till delta stratigraphy (Figure 6). However, the absence of well-defined troughs in package 3 suggests that the depositional systems may have been associated with a line source as opposed to discrete ice streams. The retrogradation at the top of unit 3.14 suggests that the grounding zone migrated landward before grounded ice readvanced to the shelf edge. In this scenario, the final erosive advance of grounding ice carved unconformity 3.14.

[19] Although units 3.12 and 3.11 exhibit an aggradational stack of subglacial sediment at Site 1097, these two units could also have been deposited as progradational systems. In this scenario, the ice sheet retreated from the shelf edge, but the grounding zone did not migrate landward of Site 1097 before grounded ice readvanced to the shelf edge. Indeed, the subglacial sediments from both the base and top of units 3.12 and 3.11 suggest that there was no

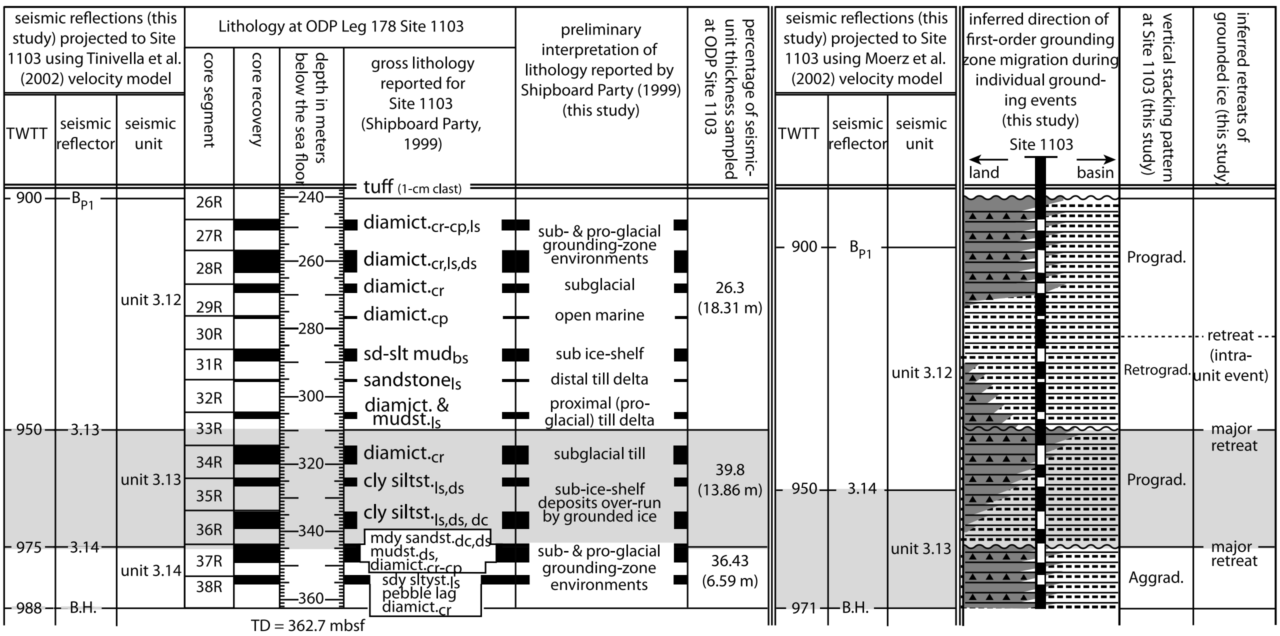

Figure 7. Correlation of seismic reflectors projected to ODP site 1103. (left) Two-way travel time (TWTT) of seismic reflectors converted to core depth using the *Tinivella et al.* [2002] velocity model. Core recovery is shown by black rectangles. The two columns to the left of the core depth log shows the lithology reported for Site 1103 [*Shipboard Scientific Party*, 1999] and our preliminary interpretation of the lithology. The following key applies to subscripts in the lithology descriptions: Cr, clast rich; cp, clast poor; ls, lamination structures; bs, bioturbation structures; ds, deformational structures; dc, dispersed clasts. Upcore lithologic changes at the well bore were used to infer directions of grounding zone migration with respect to Site 1103. The dark shading with black triangles corresponds to subglacially deposited sediment. The lighter shading with dashes corresponds to glaciomarine sediment.

period of glaciomarine sedimentation at the drill site. Conversely, given that only 2.3 m of sediment are recovered from units 3.12 and 3.11, the absence of glaciomarine sediments within the bases of these units could be fortuitous.

[20] In the case of units 3.9 and 3.2, the absence of subglacial material from the tops of these units is not surprising given the large amount of erosion indicated at the units' upper surfaces. For example at Site 1097, the erosion at the top of unconformity 3.4 has removed all seismic stratigraphic evidence of units 3.4 to 3.8 (Figures 4b and 6). It is likely that this erosion also removed subglacial sediment from the top of unit 3.9. The same argument may explain the absence of subglacial sediment from the top of unit 3.2.

[21] Seismic correlations with lithologic data do not show whether seismic reflectors are related to sharp or gradual transitions between sedimentary facies. This is because none of the seismic reflectors projects to individual core segments (Figures 6 and 7). However, glaciomarine sediment in the core segment "immediately above" a crosscutting unconformity clearly requires an overall retreat of grounded ice from the outer continental shelf. We interpret stratigraphy of this type represent major retreat of grounded ice during the package 3 time frame (Figure 6). In this study, major retreat means that the grounding zone migrated sufficiently far landward to permit glaciomarine sedimentation at Site 1097. Using this line of reasoning, major retreat of the APIS followed grounding events associated with the erosion of unconformities 3.14, 3.13, 3.10 and 3.4. The absolute magnitude of the retreat cannot be determined from the data considered in this study. Minor retreats of grounded ice are interpreted for unconformities 3.12 and 3.11 (Figure 6) because subglacial sediments directly overlie these two unconformities. Given the proximity of Site 1097 to the paleoshelf edge, these minor retreats would have been on the order of 10 to 20 km.

5.3. Twelve Shelf Edge Grounding Events Constrained to Be of Late Miocene to Early Pliocene Age

[22] The most conservative number of grounding events that occurred during package 3 time should be estimated from a single segment of the study area where stratigraphic superposition is demonstrated. On the basis of seismic evidence from the study area's south segment (Table 1), at least 16 grounding events occurred during that period as opposed to the 18 originally inferred by *Bart and Anderson* [1995]. In a synthesis of chronostratigraphic evidence, *Barker and Camerlenghi* [2002] assigned a late Miocene to early Pliocene age to those core segments corresponding to package 3. This age was based on their synthesis of diatom biozone data as well as strontium isotope ages of barnacle plates and radiometric dating of volcanic glass [*Winter and Iwai*, 2002; *Lavelle et al.*, 2002; *Di Vincenzo et al.*, 2002]. In a higher-resolution study of diatom biozones, *Iwai and Winter* [2002] assigned ages of 5.12 to 7.94 Ma for those biozones that correlate with package 3 at Site 1097. Their biozones ages are based on detailed correlations with high-resolution magnetostratigraphy for ODP Leg 178 Site 1095 [*Acton et al.*, 2002] located on the adjacent continental rise. The regional seismic framework in the south segment (Figure 4) shows that 10 of the package 3 unconformities are not present at Site 1097. However, based on stratigraphic superposition, six of these 10 reflectors (unconformities 3.1, 3.2, 3.3, 3.5, 3.8, and 3.9) are constrained to have formed within the time interval represented by that part of package 3 sampled at Site 1097 (Figure 4 and Table 1). These six reflectors plus the six reflectors penetrated at Site 1097 indicate that at least 12 grounding events occurred during 5.12 and 7.94 Ma. The oldest four grounding events (unconformities 3.15 to 3.18) are below the bottom hole depth at Site 1097 (Table 2). Thus these groundings are constrained only to be older than the oldest package 3 strata sampled at Site 1097**.** Since the base of *Actinocyclus ingens* var. *ovalis* was not reached at Site 1097, these four groundings could have occurred before 7.94 Ma.

6. Conclusions

[23] In this study, seismic-based mapping and correlations with published lithologic data provide direct evidence of at least 16 expansions of the APIS to the Pacific margin shelf edge. Correlation with published chronologic control shows that 12 of these 16 grounding events occurred between 5.12 and 7.94 Ma. These constraints on APIS glacial history should allow future investigations to better correlate these grounding events with phenomena evident from other sectors the Antarctic or from low-latitude and deep-sea records.

[24] **Acknowledgments.** This research was supported by the NSF Office of Polar Programs grant OPP-0094078 to P.J.B. Thanks to Jill Womack, Juan Chow, and Jason Holloman for comments, suggestions and assistance with drafting of figures and tables. We also thank JGR-ES Editor Robert Anderson, an anonymous Associate Editor, Eugene Domack, Mike Hambrey, and an anonymous reviewer for detailed critiques of the manuscript.

References

Acton, G. D., Y. Guyodo, S. A. Brachfeld (2002), Magnetostratigraphy of sediment drifts on the continental rise of West Antarctica (ODP Leg 178, sites 1095, 1096, and 1101), *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Alley, R. B., D. D. Blankenship, S. T. Rooney, and C. R. Bentley (1989), Sedimentation beneath ice shelves; the view from ice stream B, *Mar. Geol.*, *85*, 101–120.

Anderson, J. B. (1972), Near shore glacial-marine deposition from modern sediments of the Weddell Sea, *Nature Phys. Sci.*, *240*(104), 189–192.

Anderson, J. B., and L. R. Bartek (1992), Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information, in *The Antarctic Paleoenvironment: A Perspective on Global Change I*, *Antarct. Res. Ser.*, vol. 56, edited by J. P. Kennett and D. A. Warnke, pp. 231–263, AGU, Washington, D. C.

Anderson, J. B., D. D. Kurtz, E. W. Domack, and K. M. Balshaw (1980), Glacial and glacial marine sediments of the Antarctic continental shelf, *J. Geol.*, *88*(4), 399–414.

Anderson, J. B., C. F. Brake, and N. C. Myers (1984), Sedimentation on the Ross Sea continental shelf, Antarctica, *Mar. Geol.*, *57*, 295–333.

Anderson, J. B., L. R. Bartek, and M. A. Thomas (1991), Seismic and sedimentological record of glacial events on the Antarctic Peninsula shelf, in *Geological Evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 687–691, Cambridge Univ. Press, New York.

Antarctic Offshore Acoustic Stratigraphic Project (1995), The ANTOSTRAT Antarctic Peninsula Regional Working Group digital navigation compilation, in *Geology and Seismic Stratigraphy of the Antarctic Margin*, *Antarct. Res. Ser.*, vol. 68, edited by A. K. Cooper, P. R. Barker, and G. Brancolini, pp. A297–A301, AGU, Washington, D. C.

Barker, P. F., and A. Camerlenghi (2002), Synthesis of Leg 178 results: Glacial history of the Antarctic Peninsula from Pacific margin sediments, *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Barrett, P. J., and B. C. McKelvey (1986), Stratigraphy, in Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound, *DSIR Bull.*, *237*, 9–52.

Barrett, P. J., M. J. Hambrey, D. M. Harwood, A. R. Pyne, and P. N. Webb (1989), Synthesis, in Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound, *DSIR Bull.*, *245*, 241–251.

Barron, J. A., et al. (1991), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 119, 1003 pp., Ocean Drill. Program, College Station, Tex.

Bart, P. J., and J. B. Anderson (1995), Seismic record of glacial events affecting the Pacific margin of the northwestern Antarctic Peninsula, in *Geology and Seismic Stratigraphy of the Antarctic Margin*, *Antarct. Res. Ser.*, vol. 68, edited by A. K. Cooper, P. R. Barker, and G. Brancolini, pp. 75–95, AGU, Washington, D. C.

Bart, P. J., and J. B. Anderson (2000), Relative temporal stability of the Antarctic ice sheets during the late Neogene based on the minimum frequency of outer shelf grounding events, *Earth Planet. Sci. Lett.*, *182*, 259–272.

Bart, P. J., J. B. Anderson, F. Trincardi, and S. S. Shipp (2000), Seismic data from the Northern Basin, Ross Sea, record extreme expansions of the East Antarctic ice sheet during the late Neogene, *Mar. Geol.*, *166*, 31–50.

Bartek, L. R., P. R. Vail, J. B. Anderson, P. A. Emmet, and S. Wu (1991), Effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene, *J. Geophys. Res.*, *96*, 6753–6778.

Brancolini, G., A. K. Cooper, and F. Coren (1995), Seismic facies and glacial history in western Ross Sea (Antarctica), in *Geology and Seismic Stratigraphy of the Antarctic Margin*, *Antarct. Res. Ser.*, vol. 68, edited by A. K. Cooper, P. R. Barker, and G. Brancolini, pp. 209–233, AGU, Washington, D. C.

Canals, M., R. Urgueles, and A. M. Calafat (2000), Deep sea-floor evidence of past ice streams off the Antarctic Peninsula, *Geology*, *28*, 31–34.

Cande, S. C., and D. V. Kent (1995), Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*, 6093–6095.

Cooper, A. K., P. F. Barrett, K. Hinz, V. Traube, G. Leitchenkov, and H. M. J. Stagg (1991), Cenozoic prograding sequences of the Antarctic continental margin: A record of glacio-eustatic and tectonic events, *Mar. Geol.*, *102*, 175–213.

Cooper, A. K., S. Eittreim, U. ten Brink, and I. Zayatz (1993), Cenozoic glacial sequences of the Antarctic continental margin as recorders of Antarctic ice sheet fluctuations, in *The Antarctic Paleoenvironment: A Perspective on Global Change, Part Two*, *Antarct. Res. Ser.*, vol. 60, edited by J. P. Kennett and D. A. Warnke, pp. 75–89, AGU, Washington, D. C.

Cooper, A. K., P. E. O'Brien, and C. Richter (Eds.) (2004), *Proceedings of the Ocean Drilling Program, Scientific Results* [CD-ROM], vol. 188, Ocean Drill. Program, College Station, Tex.

Denton, G. H., M. L. Prentice, and H. Burckle (1991), Cainozoic history of the Antarctic Ice Sheet, in *The Geology of Antarctica*, edited by R. J. Tingey, pp. 365–463, Clarendon, Oxford, U. K.

De Santis, L., J. B. Anderson, G. Brancolini, and I. Zayatz (1995), Seismic record of late Oligocene through Miocene glaciation on the central and eastern continental shelf of the Ross Sea, in *Geology and Seismic Stratigraphy of the Antarctic Margin*, *Antarct. Res. Ser.*, vol. 68, edited by A. K. Cooper, P. R. Barker, and G. Brancolini, pp. 235–260, AGU, Washington, D. C.

Di Vincenzo, G., A. Caburlotto, and A. Camerlenghi (2002), ^{40}Ar-^{39}Ar investigation of volcanic clasts in glaciogenic sediments at sites 1097 and 1103 (ODP Leg 178, Antarctic Peninsula), *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Domack, E. W. (1982), Sedimentology of glacial and glacial marine deposits on the George V-Adelie continental shelf, East Antarctica, *Boreas*, *11*(1), 79–97.

Domack, E. W., E. K. Jacobson, S. Shipp, and J. B. Anderson (1999), Late Pleistocene-Holocene retreat of the West Antarctic Ice Sheet System in the Ross Sea: Part 2. Sedimentologic and stratigraphic signature, *Geol. Soc. Am. Bull.*, *111*, 1517–1536.

Dowdeswell, J. A., C. Ó. Cofaigh, and C. J. Pudsey (2004), Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream, *Geology*, *32*, 13–16.

Dunbar, R. B., J. B. Anderson, E. W. Domack, and S. S. Jacobs (1985), Oceanic influences on sedimentation along the Antarctic continental shelf, in *Oceanology of the Antarctic Continental Shelf*, *Antarct. Res. Ser.*, vol. 43, edited by S. S. Jacob, pp. 291–312, AGU, Washington, D. C.

Eittreim, S. L., A. K. Cooper, and J. Wannesson (1995), Seismic stratigraphic evidence of ice-sheet advances on the Wilkes Land margin of Antarctica, *Sediment. Geol.*, *96*(1–2), 131–156.

Elverhøi, A. (1981), Evidence for a late Wisconsin glaciation of the Weddell Sea, *Nature*, *293*, 641–642.

Eyles, N., J. Daniels, L. E. Osterman, and N. Januszcak (2001), Ocean Drilling Program Leg 178 (Antarctic Peninsula): Sedimentology of glacially influenced continental margin topsets and foresets, *Mar. Geol.*, *178*, 135–156.

Hambrey, M. J. (1993), Cenozoic sedimentary and climatic record, Ross Sea region, Antarctica, in *The Antarctic Paleoenvironment: A Perspective on Global Change, Part Two*, *Antarct. Res. Ser.*, vol. 60, edited by J. P. Kennett and D. A. Warnke, pp. 91–124, AGU, Washington, D. C.

Hambrey, M. J., W. U. Ehrmann, and B. Larsen (1991), Cenozoic glacial record of the Prydz Bay continental shelf, East Antarctica, *Proc. Ocean Drill. Program Sci. Results*, *119*, 77–132.

Harwood, D. M., and T. Maruyama (1992), Middle Eocene to Pleistocene diatom biostratigraphy of Southern Ocean sediments from the Kerguelen Plateau, Leg 120, *Proc. Ocean Drill. Program Sci. Results*, *120*, 683–733.

Hayes, D. E., and L. A. Frakes (1975), General Synthesis, Deep Sea Drilling Project 28, *Initial Rep. Deep Sea Drill. Proj.*, *28*, 919–942.

Heroy, D. C., and J. B. Anderson (2003), Last Glacial Maximum (LGM) ice sheet reconstruction and glacial retreat history of Antarctic Peninsula, paper presented at XVI INQUA Congress, Int. Union for Quat. Res., Reno, Nev., 23–30 July.

Howat, I. M., and E. W. Domack (2003), Reconstructions of western Ross Sea palaeo-ice-stream grounding zones from high-resolution acoustic stratigraphy, *Boreas*, *32*, 56–75.

Iwai, M., and D. Winter (2002), Data Report: Taxonomic Notes on Neogene Diatoms from the western Antarctic Peninsula: Ocean Drilling Program Leg 178, *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Kellogg, T. B., R. S. Truesdale, and L. E. Osterman (1979), Late Quaternary extent of the West Antarctic ice sheet; new evidence from Ross Sea cores, *Geology*, *7*, 249–253.

Kennedy, D. S., and J. B. Anderson (1989), Glacial-marine sedimentation and Quaternary glacial history of Marguerite Bay, Antarctic Peninsula, *Quat. Res.*, *31*(2), 255–276.

Larter, R. D., and P. F. Barker (1989), Seismic stratigraphy of the Antarctic Peninsula Pacific margin: a record of Pliocene-Pleistocene ice volume and paleoclimate, *Geology*, *17*, 731–734.

Larter, R. D., and A. P. Cunningham (1993), The depositional pattern and distribution of glacial-interglacial sequences on the Antarctic Peninsula Pacific Margin, *Mar. Geol.*, *109*, 203–219.

Larter, R. D., and L. E. Vanneste (1995), Relict subglacial deltas on the Antarctic Peninsula outer shelf, *Geology*, *23*, 33–36.

Larter, R. D., M. Rebesco, L. E. Vanneste, L. A. P. Gamboa, and P. Barker (1997) Cenozoic tectonic, sedimentary and glacial history of the continental shelf west of Graham Land, Antarctic Peninsula, in *Geology and Seismic Stratigraphy of the Antarctic Margin*, *Part 2*, *Antarct. Res. Ser.*, vol. 71, edited by A. K. Cooper, P. F. Barker, and G. Brancolini, pp. 1–27, AGU, Washington, D. C.

Lavelle, M., P. F. Barker, and L. E. Osterman (2002), Data report: Strontium isotope dating of barnacle fragments: Antarctic Peninsula Site 1103, *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Licht, K. J., A. E. Jennings, J. T. Andrews, and K. M. Williams (1996), Chronology of late Wisconsin ice retreat from the western Ross Sea, Antarctica, *Geology*, *24*, 223–226.

Marchant, D. R., G. H. Denton, and C. C. Swisher III (1993), Miocene-Pliocene-Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica, *Geogr. Ann.*, *75A*, 269–302.

Moerz, T., R. Laronga, C. Lauer-Leredde, C. Escutia, and T. C. W. Wolf-Welling (2002), Composite velocity profile of shelf Site 1103 (ODP Leg 178, western Antarctic Peninsula), *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Moons, A., M. De Batist, J. P. Henriet, and H. Miller (1992), Sequence stratigraphy of Crary Fan southeastern Weddell Sea, in *Recent Progress in Antarctic Earth Science*, edited by Y. Yoshida, K. Kaminuma, and K. Shiraishi, pp. 613–618, Terra Sci., Tokyo.

Pope, P. G., and J. B. Anderson (1992), Late Quaternary glacial history of the northern Antarctic Peninsula's western continental shelf: Evidence from the marine record, in *Contributions to Antarctic Research III*, *Antarct. Res. Ser.*, vol. 57, edited by D. H. Elliot, pp. 63–91, AGU, Washington, D. C.

Pudsey, C. J., P. F. Barker, and R. D. Larter (1994), Ice sheet retreat from the Antarctic Peninsula shelf, *Cont. Shelf Res.*, *14*, 1647–1675.

Rebesco, M., A. Camerlenghi, L. DeSantis, E. W. Domack, and M. E. Kirby (1998), Seismic stratigraphy of Palmer Deep: A fault-bounded Late Quaternary sediment trap on the inner continental shelf, Antarctic Peninsula Pacific margin, *Mar. Geol.*, *151*, 89–110.

Shipboard Scientific Party (1999), Leg 178 summary, *Proc. Ocean Drill. Program Initial Rep.* [CD-ROM], *178*.

Shipp, S., J. B. Anderson, and E. W. Domack (1999), Seismic signature of the Late Pleistocene fluctuation of the West Antarctic Ice Sheet, *Geol. Soc. Am. Bull.*, *111*, 1486–1516.

Tinivella, U., A. Camerlenghi, and M. Rebesco (2002), Data report: Seismic velocity analysis on the continental shelf transect, ODP Leg 178, Antarctic Peninsula, *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

Vanneste, L. E., and R. D. Larter (1995), Deep-tow boomer survey on the Antarctic Peninsula Pacific margin: An investigation of the morphology and acoustic characteristics of Late Quaternary sedimentary deposits on the outer continental shelf and upper slope, in *Geology and Seismic Stratigraphy of the Antarctic Margin*, *Antarct. Res. Ser.*, vol. 68, edited by A. K. Cooper, P. R. Barker, and G. Brancolini, pp. 97–121, AGU, Washington, D. C.

Vanney, J. R., and G. L. Johnson (1974), Source Geomorphology of the Pacific continental margin of the Antarctic Peninsula, *Initial Rep. Deep Sea Drill. Proj.*, *35*, 279–289.

Winter, D., and M. Iwai (2002), Neogene diatom biostratigraphy, Antarctic Peninsula Pacific Margin, ODP Leg 178 rise sites, *Proc. Ocean Drill. Program Sci. Results* [CD-ROM], *178*.

P. J. Bart, D. Egan, and S. A. Warny, Department of Geology and Geophysics, Louisiana State University, Howe-Russell Geoscience Complex, E235, Baton Rouge, LA 70803 USA. (pbart@geol.lsu.edu)