Margin architecture reveals the transition to the modern Antarctic ice sheet ca. 3 Ma

Michele Rebesco Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42/C, 34010 Sgonico (TS), Italy

Angelo Camerlenghi Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42/C, 34010 Sgonico (TS), Italy, and Institució Catalana de Recerca i Estudis Avançats, c/o GRC Geociències Marines, Departament d'Estratigrafia, P. i Geociències Marines, Universitat de Barcelona, C/ Martí i Franquès, s/n, E-08028 Barcelona, Spain

Riccardo Geletti Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42/C, 34010 Sgonico (TS), Italy

Miquel Canals GRC Geociències Marines, Departament d'Estratigrafia, P. i Geociències Marines, Universitat de Barcelona, C/ Martí i Franquès, s/n, E-08028 Barcelona, Spain

ABSTRACT

Seismic reflection data collected primarily on the continental slope of the Pacific margin of the Antarctic Peninsula after drilling Ocean Drilling Program (ODP) Leg 178 allow us to date a regional change in the style of margin accretion to ca. 3 Ma. Late Pliocene deep erosion of continental shelf and slope, which likely included the emplacement of a megadebris-flow deposit, was followed by prominent growth of steep, relatively stable continental slope prograding wedges, while the deep distal margin sedimentation rate was significantly reduced. A review of the available stratigraphy from Deep Sea Drilling Project–ODP drilling, and correlation with available seismic stratigraphic information, allowed us to recognize comparable changes in terms of age and trends in continental margin evolution in several places around Antarctica. We argue that this late Pliocene architectural change of the Antarctic margin reflects a change in the texture and water content of the sediment delivered by the Antarctic ice sheet following the transition from wet- to dry-based ice regimes. This circum-Antarctic change coincides with the late Pliocene (ca. 3 Ma) global cooling and is proposed as the marker event of the transition to the modern cold polar dry-based Antarctic ice sheet.

Keywords: Antarctic ice sheet, Antarctic Peninsula, reflection seismic data, Ocean Drilling Program, late Pliocene, continental margin sedimentation.

INTRODUCTION

Antarctica exerts a major influence on global climate and sea level (Blunier et al., 1998; Stephens and Keeling, 2000). Knowledge of the behavior of the past Antarctic ice sheet provides an important framework for understanding climate change. The Antarctic ice sheet is inferred to have undergone a change from an earlier polythermal dynamic ice regime to the modern cold and relatively stable one, but the timing and circumstances of this switch have been controversial subjects for more than 20 yr. The Antarctic ice sheet has been inferred alternatively as (1) permanently cold and stable since the middle Miocene (e.g., Denton et al., 1993; Flower and Kennett, 1994); (2) predominantly cold and stable after the middle Miocene but with periods of increased dynamicism in the Pliocene (e.g., Barrett et al., 1992; Bart, 2001) and in the late Pleistocene (Scherer et al., 2000); and (3) cold polar and stable later than the middle Miocene (e.g., late Miocene: Armienti and Baroni, 1999; late Pliocene: Webb and Harwood, 1991; Hambrey and McKelvey, 2000). The evidence for the early stages of the Antarctic glaciation in the Oligocene and middle Miocene (East and West Antarctica, respectively) was only partially substantiated by sampling of the proximal continental margin (Barker and Camerlenghi, 2002; Cooper and O'Brien, 2004).

The hitherto missing stratigraphic link between the highly discontinuous, poorly dated proximal strata deposited by the grounded ice on the continental shelf and the continuous, relatively well dated distal strata on the continental rise is considered a key factor in the reconstruction of the history of the Antarctic ice sheet (e.g., Barker et al., 1999). Here we present the analysis of seismic reflection data, collected primarily on the continental slope of the Pacific margin of the Antarctic Peninsula (PMAP) after Ocean Drilling Program (ODP) Leg 178, that allow us to identify a change in the style of sedimentary progradation ca. 3 Ma. We argue that this change, which appears coeval in the six most studied sectors of the West and East Antarctic margins, marks the growth of a cold-based Antarctic ice sheet like the modern one.

METHODS

High-resolution multichannel seismic (MCS) reflection profiles (Corrientes de Hielo Marin/Sediment Drift of the Antarctic Offshore Scientific Party [COHIMAR/SEDANO], 2003) were collected with a 96 channel, 600-m-long analog streamer (intertrace 6.5 m) towed between 2 and 4 m from the sea surface. Energy was provided by two GI guns with a volume of 150 in^3 (2458 cm^3) each. Data sampling was 2 ms. Processing included band-pass and notch filtering, sorting, de-bias, velocity analysis, normal move out, mute, stacking, Stolt time migration, and balancing. Correlation and stratigraphic analyses were performed using Deep Sea Drilling Project (DSDP) and ODP data available from published reports.

ARCHITECTURAL CHANGES IN THE ANTARCTIC PENINSULA PACIFIC MARGIN

The outer continental shelf of the PMAP is underlain by seaward-prograding sedimentary wedges mainly composed of late Miocene–Pleistocene diamicts (Barker and Camerlenghi, 2002), and is dissected by a number of modern, U-shaped, glacial troughs tens of kilometers wide (Rebesco et al., 1998). The MCS profiles collected along the upper continental slope enabled us to identify a 20-km-wide glacial paleotrough filled by prograding strata as thick as 1 km beneath the present-day Biscoe Trough (Fig. 1; see Data Repository Fig. DR1[1]). A regional discontinuity, marking the base of other coeval paleotroughs beneath modern glacial troughs, correlates with the boundary that separates the previously identified Pliocene–Pleistocene sequences

[1]GSA Data Repository item 2006061, Figures DR1 and DR2, multichannel seismic reflection profiles, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

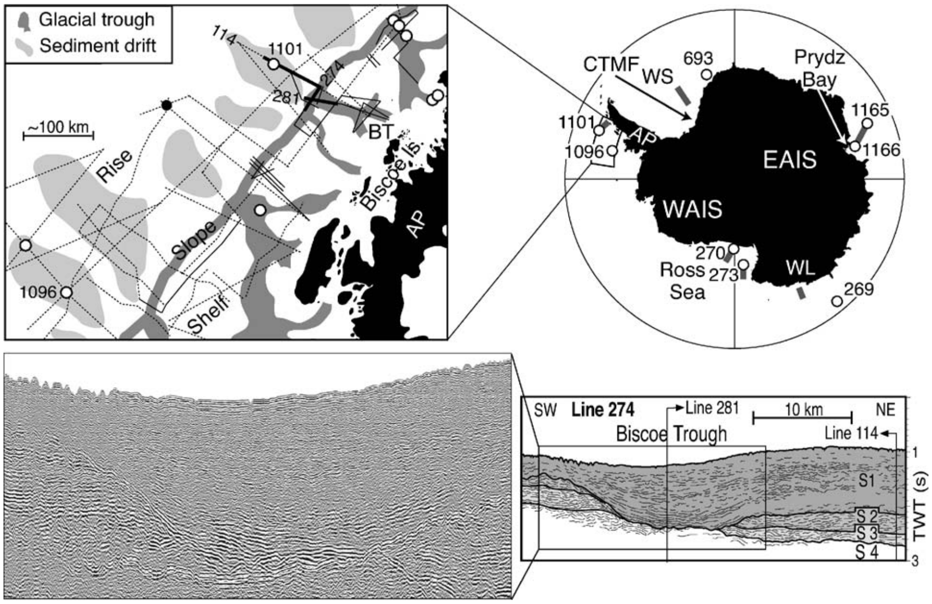

Figure 1. Time-migrated seismic reflection profile 274 collected along continental slope across Biscoe glacial trough, with our interpretation. Unit S1 was deposited by a grounded ice sheet above regional erosional surface dated as 2.9 ± 0.2 Ma that marks change in stratal geometries. Inset: Location of Pacific margin of Antarctic Peninsula (PMAP), with borehole and seismic reflection data location (continuous lines—high-resolution seismic profiles; thicker lines—profiles shown herein). AP—Antarctic Peninsula; BT—Biscoe Trough; WAIS—West Antarctic Ice Sheet; EAIS—East Antarctic Ice Sheet; WS—Weddell Sea; CTMF—Crary Trough mouth fan; WL—Wilkes Land; TWT—two-way traveltime.

S1 and S2. Both sequences are characterized by steeply seaward dipping strata that we infer to have been deposited at the grounding line of the ice sheet (Larter and Barker, 1989). Although the lack of data prevents unambiguous long-distance correlations along the inner shelf, this boundary is recognized on most profiles crossing the outer shelf. In the new MCS data, the S1-S2 boundary can be traced from the shelf to the base of the slope as a pronounced downlap surface (Fig. 2; Fig. DR2), and then as a disconformity to ODP Site 1101 that is over a deep-sea sediment drift on the continental rise. At Site 1101, the S1-S2 boundary correlates with the independently identified M1-M2 seismic boundary (Rebesco et al., 1997). Sediments directly above M1-M2 are within magnetic chron C2An.1n (2.58–3.04 Ma). Diatom stratigraphy suggests that the M1-M2 boundary is close to the onset of the *Thalassiosira insigna–T. vulnifica* zone. By linear interpolation of the late Pliocene sedimentation rate at ODP Site 1101, we estimate the age of the boundary as 2.9 ± 0.2 Ma. The M1-M2 boundary may also be correlated along the continental rise within our seismic data set to ODP Site 1096, where it is in the same magnetostratigraphic and biostratigraphic level as in Site 1101, confirming the isochronous nature along the margin of the M1-M2 boundary and of the disconformity correlative to it.

The distinct change in stratal geometry at the S1-S2 horizon is coeval with the emplacement of a megadebris-flow deposit on the continental rise that resulted from a failure of the continental slope (Diviacco et al., 2006). A gradual, though significant, change in the continental rise sedimentation rates is seen across the M1-M2 boundary. Relatively high sedimentation rate during the warmer early Pliocene shifted to much lower during the colder late Pliocene and Pleistocene (e.g., from 180 to 80 m/m.y. at Site 1096). Given the tectonic quiescence of this part of the margin, and the lack of evidence for changes in the bottom current regime, the decrease in sedimentation rate on the continental rise is viewed as due to less terrigenous sediment being supplied from the shelf (Barker and Camerlenghi, 2002, and references therein).

COMPARABLE CHANGES IN OTHER ANTARCTIC CONTINENTAL MARGINS

In order to determine whether this is a regional event, or an Antarctic-wide marker

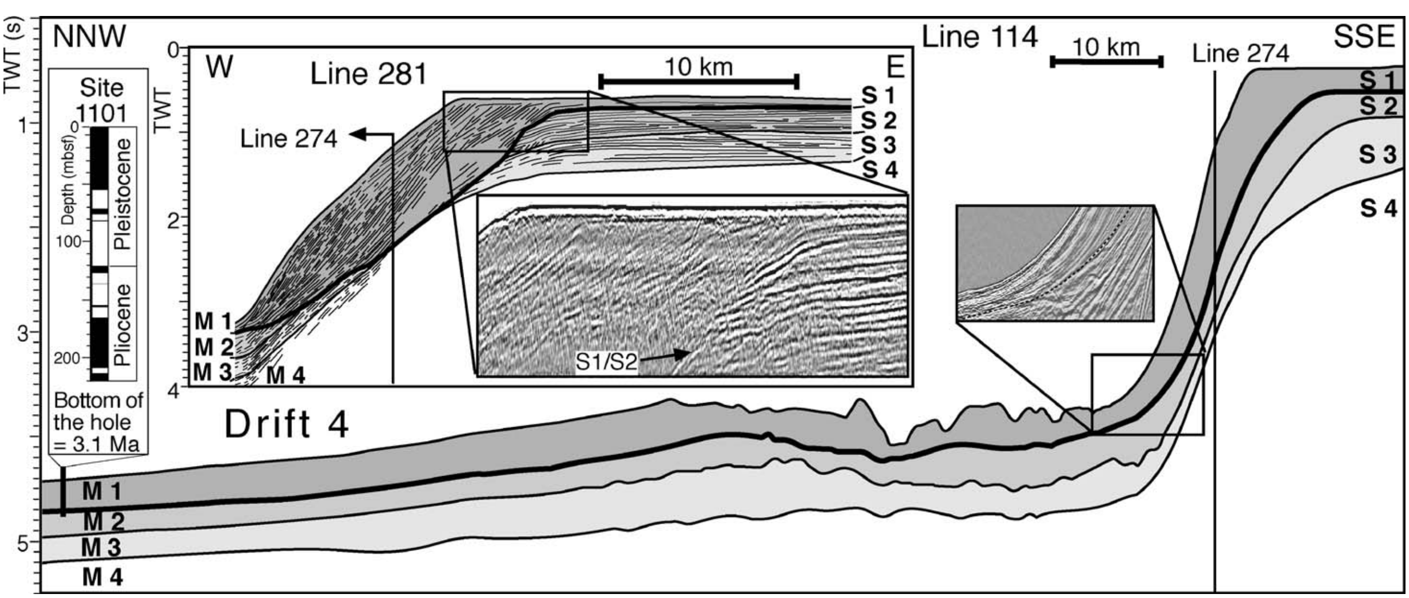

Figure 2. Continental margin stratigraphy shown in stacked seismic reflection profiles collected across margin, with our interpretation. Profiles 281 and 114 are available in the Data Repository (see footnote 1). Common change in stratal geometries following Pliocene (2.9 ± 0.2 Ma) regional erosional event is to high-angle foreset beds that downlap onto S1-S2. TWT—two-way traveltime.

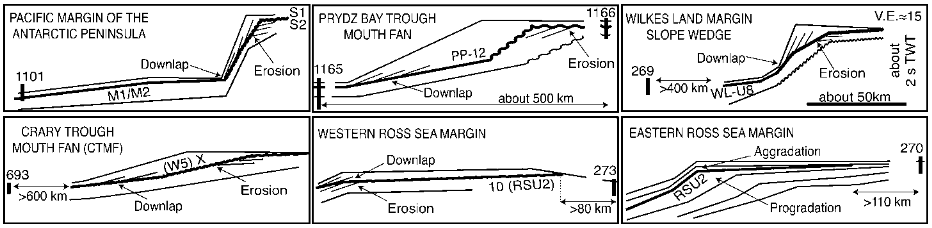

Figure 3. Simplified models of continental margin development illustrated by stratal geometries in six key sectors of East and West Antarctica continental margin: Antarctic Peninsula margin, from seismic refection profile 114 (Data Repository; see footnote 1); Wilkes Land margin, from profile WGA-35 (De Santis et al., 2003); Prydz Bay Trough, from composite profile (Cooper and O'Brien, 2004); Crary Trough mouth fan, from profiles AWI 90190 and 90–110 (Oszkó, 1997); western Ross Sea margin, from profile 37 (Bart et al., 2000); and eastern Ross Sea margin, from profile BGR 7 (De Santis et al., 1995). TWT—two-way traveltime.

event, we analyzed the existing stratigraphic information on late Neogene continental margin deposits of both East and West Antarctica.

In the Prydz Bay region (Fig. 1), widespread post–early Pliocene erosion of the continental shelf and adjacent Lambert graben resulted in the excavation of a paleotrough along seismic reflection surface PP12 beneath the modern Prydz Channel (Cooper and O'Brien, 2004). Eroded sediments were largely deposited in the Prydz Trough mouth fan (PTMF) and contributed to the rapid progradation of the shelf edge (Fig. 3). We consider the late Neogene evolution of the PTMF as the marine sedimentary response to the development of a cold stable East Antarctic Ice Sheet (onland studies; Hambrey and McKelvey, 2000). According to results of drilling continental shelf Site 1166, rapid progradation began prior to the deposition of two thin diatomaceous beds within massive glacial diamictons, the lower dated between 2.5–2.7 and 2.7–3.2 Ma. Similar diatomaceous beds, thought to record short periods of reduced sea-ice cover during glacial retreat, were dated as Pliocene in Site 742 (Hambrey and McKelvey, 2000) and in Site 739, where they delimit the early Pliocene age of surface PP-12 (Cooper and O'Brien, 2004). In the decreasing continental rise sedimentation rate observed at Site 1165, a rapid change from ~15 to 7 m/m.y. occurs in the *T. insigna–T. vulnifica* subzone a, within the lower part of magnetic chron C2An.1n. We infer that this change in sediment rates corresponds to the landward shift of the glacigenic sedimentation depocenter to the upper slope. As such it is similar to and coeval with (±0.2 m.y.) the rate changes and depocenter shifts identified in the PMAP.

In the Weddell Sea, the Crary Trough (Fig. 1) is a broad depression of the shelf resulting from glacial erosion at the convergence of several East Antarctic ice streams. The Neogene development of the Crary Trough mouth fan (CTMF) resulted in prominent progradation of a sedimentary wedge marked by stratal downlapping at the base of the continental slope (Fig. 3). A phase of major fan outbuilding followed early to late Pliocene erosion of the margin (margin collapse; after Bart et al., 1999). The deep-sea record of Site 693 (and other sites of ODP Leg 113) shows an abrupt decrease in the regional sedimentation rate and in diatom abundance ca. 3 Ma (Kennett and Barker, 1990). This decrease is the youngest prominent change in the sediment accumulation in this margin. We believe (in agreement with Oszkó, 1997) that it is coeval with the beginning of pronounced progradation of the CTMF.

The Wilkes Land margin of East Antarctica (Fig. 1) prograded, with steep forest beds that downlap onto a regional seismic unconformity WL-U8 (Fig. 3), inferred to be Pliocene (De Santis et al., 2003) on the basis of indirect facies correlation with DSDP Site 269. The unconformity also marks erosion on the continental shelf and stratal downlapping at the base of the slope. The thin sediment cover of the continental rise above WL-U8 suggests (in agreement with De Santis et al., 2003) that sediment accumulation rates there have been low during Pliocene–Pleistocene time, and indicate a relatively low supply of sediments being provided to the continental rise (Barker, 1995; Escutia et al., 2000). The Pliocene–Pleistocene sediment depocenter is focused beneath the outer shelf and slope as subglacially derived debris-flow deposits (De Santis et al., 2003).

On the outer shelf of the western Ross Sea (Fig. 1), late Neogene clinoforms downlap onto the deep, widespread erosional unconformity RSU2 (Brancolini et al., 1995) or 10 (Bart et al., 2000), the age of which is estimated as between middle Miocene and late Pliocene on the basis of poor-recovery data of DSDP Site 273 (Fig. 3). This unconformity marks a distinct change in seismic character and continental margin architecture resulting from massive ice streams eroding wide troughs on the shelf. Thick fans developed locally at the mouths of the troughs with abrupt downslope pinchouts. In the eastern Ross Sea (Fig. 1), unconformity RSU2 marks the transition from margin progradation to aggradation, and there is no evidence of stratal pinchout and downlapping above the unconformity (Fig. 3). Despite this difference between the eastern Ross Sea and the other five Antarctic continental margins analyzed, RSU2 unquestionably marks the latest distinct change in continental margin architecture. The reason for this difference might be that most of the West Antarctic Ice Sheet drainage area into the eastern Ross Sea is grounded below sea level. Consequently, the response of the ice sheet to climatic changes is expected to be different from that of the ice sheet grounded above sea level.

The late Neogene architectural development of the Antarctic continental margin is characterized by: (1) enhanced progradation in the form of steep sedimentary wedges building above pronounced truncation surfaces; (2) prominent downlapping of these wedges at the base of the continental slope; and (3) significant decrease in sedimentation rates on the continental rise.

DISCUSSION

We suggest that the apparent abrupt late Pliocene changes in stratal geometries and sedimentation rates on the continental margin result from a change in the Antarctic ice sheet to a cold, dry-base glacier system. After the change, meltwater persisted only at the bases of a few large ice streams; sediment delivery was concentrated at the mouths of these (such as the Crary and Prydz fans of East Antarctica). Focused sediment load and faster progradation of sedimentary wedges induced an early failure of the continental slope that included major sediment sliding and margin collapse (Diviacco et al., 2006; Bart et al., 1999); the resulting regional erosional surfaces can be recognized all around Antarctica. Proximal depocenters developed beneath the continental slope: the sediments were deposited from grounded ice with limited basal meltwater at the shelf edge, were coarser and less sorted than previously, and had higher resistance to shear stress. The continental slope became increasingly steeper and sediment transport was preferentially short run-out debris flows. Consequently, the continental rise was progressively deprived of terrigenous sediments.

We believe that the transition from the polythermal, dynamic, and cyclic Antarctic ice sheet to the polar ice sheet of today is recorded by the change in continental margin architecture, which coincided with the late Pliocene global cooling. Such change occurred at the same time, 2.75 Ma, as the onset of the Northern Hemisphere glaciation (e.g., Lear et al., 2000). Margin architecture has remained mostly unchanged since the late Pliocene, and further indicates to us that the Antarctic ice sheet has been relatively stable since then.

Global increases in sedimentation rates as well as coarsening in all middle- to low-latitude continental margins from 4 to 2 Ma have been interpreted as a transition from a period of climate stability to a time of frequent and abrupt changes in temperature, precipitation, and vegetation, that prevented fluvial and periglacial systems from establishing equilibrium states (Peizhen et al., 2001). Conversely, scientific drilling of the deep-water Antarctic margin shows the opposite trend, with decreasing sedimentation rates in the Pliocene–Quaternary leading to present-day sediment starvation (e.g., Barker, 1995; Barker and Camerlenghi, 2002; Cooper and O'Brien, 2004). According to our evidence, the East Antarctic Ice Sheet and West Antarctic Ice Sheet switched to the present full polar conditions ca. 3 Ma, concomitant with the global onset of climatic instability. We suggest that the response of the extraordinarily large Antarctic subglacial sedimentary systems to global climatic changes became too slow to cope with the increased frequency and magnitude of the changes in the Pleistocene and Quaternary climatic forcing. This inference is supported by modeling studies that demonstrate how the progressive decline of atmospheric carbon dioxide concentration caused feedback mechanisms that forced the Antarctic ice sheet to grow and become less sensitive to orbital forcing (DeConto and Pollard, 2003) than before.

ACKNOWLEDGMENTS

Research was conducted within the joint Sediment Drift of the Antarctic Offshore (SEDANO) and Corrientes de Hielo Marin (COHIMAR) projects funded by the Italian Programma Nazionale di Ricerche in Antartide and the Spanish Antarctic Program. Comments provided by Alan Cooper, Tim Naish, and anonymous reviewers contributed to the final draft of this manuscript.

REFERENCES CITED

Armienti, P., and Baroni, C., 1999, Cenozoic climatic change in Antarctica recorded by volcanic activity and landscape evolution: Geology, v. 27, p. 617–620.

Barker, P.F., 1995, The proximal marine sediment record of Antarctic climate since the late Miocene, *in* Cooper, A.K., et al., eds., Geology and seismic stratigraphy of the Antarctic Margin: American Geophysical Union Antarctic Research Series, v. 68, p. 25–57.

Barker, P.F., and Camerlenghi, A., 2002, Glacial history of the Antarctic Peninsula from Pacific margin sediments, *in* Barker, P.F., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 178: College Station, Texas, Ocean Drilling Program: http://www-odp.tamu.edu/publications/178_SR/synth/synth.htm (accessed October 2002).

Barker, P.F., Barrett, P.J., Cooper, A.K., and Huybrechts, P., 1999, Antarctic glacial history from numerical models and continental margin sediments: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 150, p. 247–267.

Barrett, P.J., Adams, C.J., McIntosh, W.C., Swisher, C.C., III, and Wilson, G.S., 1992, Geochronological evidence supporting Antarctic deglaciation three million years ago: Nature, v. 359, p. 816–818.

Bart, P.J., 2001, Did the Antarctic ice sheets expand during the early Pliocene?: Geology, v. 29, p. 67–70.

Bart, P.J., DeBatist, M., and Jokat, W., 1999, Interglacial collapse off Crary Trough Mouth Fan, Weddell Sea, Antarctica: Implications for Antarctic glacial history: Journal of Sedimentary Research, v. 69, p. 1276–1289.

Bart, P.J., Anderson, J.B., Trincardi, F., and Shipp, S.S., 2000, Seismic data from the Northern basin, Ross Sea, record extreme expansions of the East Antarctic Ice Sheet during the late Neogene: Marine Geology, v. 166, p. 31–50.

Blunier, T., Chappellaz, J., Schwander, J., Dällenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U., and Johnsen, S.J., 1998, Asynchrony of Antarctic and Greenland climate change during the last glacial period: Nature, v. 394, p. 739–743.

Brancolini, G., Cooper, A.K., and Coren, F., 1995, Seismic facies and glacial history in the western Ross Sea (Antarctica), *in* Cooper, A.K., et al., eds., Geology and seismic stratigraphy of the Antarctic Margin: American Geophysical Union Antarctic Research Series, v. 68, p. 209–234.

Corrientes de Hielo Marin/Sediment Drift of the Antarctic Offshore (COHIMAR/SEDANO) Scientific Party, 2003, Uncovering the footprint of former ice streams off Antarctica: Eos (Transactions, American Geophysical Union), v. 84, p. 97–108.

Cooper, A.K., and O'Brien, P.E., 2004, Leg 188 synthesis: Transitions in the glacial history of the Prydz Bay region, East Antarctica, from ODP drilling, *in* Cooper, A.K., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 188: College Station, Texas, Ocean Drilling Program: http://www-odp.tamu.edu/publications/188_SR/synth/synth.htm (accessed July 2004).

DeConto, R.M., and Pollard, D., 2003, Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2: Nature, v. 421, p. 245–249.

Denton, G.H., Sugden, D.E., Marchant, D.R., Hall, B.L., and Wilch, T.I., 1993, East Antarctic ice sheet sensitivity to Pliocene climate change from a Dry Valleys perspective: Geografiska Annaler, v. 75A, p. 155–204.

De Santis, L., Anderson, J.B., Brancolini, G., and Zayatz, I., 1995, Seismic record of late Oligocene through Miocene glaciation on the central and eastern continental shelf of the Ross Sea, *in* Cooper, A.K., et al., eds., Geology and seismic stratigraphy of the Antarctic Margin: American Geophysical Union Antarctic Research Series, v. 68, p. 235–260.

De Santis, L., Brancolini, G., and Donda, F., 2003, Seismo-stratigraphic analysis of the Wilkes Land continental margin (East Antarctica): Influence of glacially driven processes on the Cenozoic deposition: Deep Sea Research, v. 50, part II, p. 1563–1594.

Diviacco, P., Rebesco, M., and Camerlenghi, A., 2006, Late Pliocene mega debris flow deposit and related fluid escapes identified on the Antarctic Peninsula continental margin by seismic reflection data analysis: Marine Geophysical Researches, v. 27 (in press).

Escutia, C., Eittreim, S.L., Cooper, A.K., and Nelson, C.H., 2000, Morphology and acoustic character of the Antarctic Wilkes Land turbidite systems; ice-sheet-sourced versus river-sourced fans: Journal of Sedimentary Research, v. 70, p. 84–93.

Flower, B.P., and Kennett, J.P., 1994, The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation, and global carbon cycling: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 108, p. 537–555.

Hambrey, M.J., and McKelvey, B., 2000, Neogene fluctuations of the East Antarctic Ice Sheet: Stratigraphic evidence from the Lambert Glacier region: Geology, v. 28, p. 887–890.

Kennett, J.P., and Barker, P.F., 1990, Latest Cretaceous to Cenozoic climate and oceanographic developments in the Weddell Sea, Antarctica: An ocean-drilling perspective, *in* Kennett, J.P., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 113: College Station, Texas, Ocean Drilling Program, p. 937–960.

Larter, R.D., and Barker, P.F., 1989, Seismic stratigraphy of the Antarctic Peninsula Pacific margin: A record of Pliocene–Pleistocene ice volume and paleoclimate: Geology, v. 17, p. 731–734.

Lear, C.H., Elderfield, H., and Wilson, P.A., 2000, Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite: Science, v. 287, p. 269–272.

Oszkó, L., 1997, Tectonic structures and glaciomarine sedimentation in the south-eastern Weddell Sea from seismic reflection data: Berichte zur Polarforschung, v. 222, 153 p.

Peizhen, Z., Molnar, P., and Downs, W.R., 2001, Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change and erosion rates: Nature, v. 410, p. 891–897.

Rebesco, M., Larter, R.D., Barker, P.F., Camerlenghi, A., and Vanneste, L.E., 1997, The history of sedimentation on the continental rise west of the Antarctic Peninsula, *in* Cooper, A.K., and Barker, P.F., eds., Geology and seismic stratigraphy of the Antarctic Margin 2: American Geophysical Union Antarctic Research Series, v. 71, p. 28–49.

Rebesco, M., Camerlenghi, A., and Zanolla, C., 1998, Bathymetry and morphogenesis of the continental margin west of the Antarctic Peninsula: Terra Antartica, v. 5, p. 715–725.

Scherer, R.P., Aldahan, A.A., Tulaczyk, S., Possnert, G., Engelhardt, H., and Kamb, B., 2000, Pleistocene collapse of the West Antarctic ice sheet: Science, v. 281, p. 82–85.

Stephens, B.B., and Keeling, R.F., 2000, The influence of Antarctic sea ice on glacial-interglacial CO_2 variations: Nature, v. 404, p. 171–174.

Webb, P.-N., and Harwood, D.M., 1991, Late Cenozoic glacial history of the Ross Sea Embayment, Antarctica: Quaternary Science Reviews, v. 10, p. 215–223.

Manuscript received 27 June 2005
Revised manuscript received 16 November 2005
Manuscript accepted 16 December 2005

Printed in USA