Antarctic seismic stratigraphy

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Summary This report provides a brief overview of Antarctic seismic reflection surveys, and how they are used to map Antarctic seismic stratigraphy and, inconjunction with drilling data, help decipher geologic and glacial histories of circum-Antarctic offshore regions.

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Introduction

In contrast to proxy-based approaches to global climatic and ice-volume changes 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), reconstructing a detailed high-resolution Antarctic glacial history from direct seismic-stratigraphic evidence on the continental margins is extremely difficult. One problem is that the deposits and land-surface morphology created during a cycle of ice-sheet advance and retreat can be stripped away during subsequent cycles. In addition, dating the Antarctic glacial deposits is problematic because the virtual lack of calcareous microfossils and the common occurrence of reworked siliceous microfossils (e.g., Barrett, 1996). The challenge is to find a continuous, datable and high-resolution record close enough to the continent that the adjacent region's glacial history can be unambiguously interpreted irrespective of other processes at distal locations that might mainly reflect global paleoclimatic and paleoceanographic changes.

The primary issue addressed in this section of the workshop concerns the glacial-history interpretation of seismic data grids acquired on Antarctica's outer continental shelves. On the margins, seismic-based investigations have focused on two temporal scales: 1) Ice-sheet retreat and dynamics post-dating the last glacial maximum (LGM) and 2) Major ice-sheet dynamics throughout the Cenozoic. Since the deposits associated with the LGM are relatively thin and at the seafloor, investigators have primarily used high-resolution seismic data to determine the back-stepping pattern of ice-sheet grounding zones (e.g., Shipp et al., 1999). Seismic-based interpretations are usually tested against lithologic and chronologic data obtained in piston core samples (e.g., Domack et al, 1999).

To evaluate glacial history over longer intervals of geologic time, investigators have generally designed seismic acquisition plans that image deeper subsurface levels (e.g., ANTOSTRAT, 1995). These seismic grids have low to intermediate resolution but in some cases, high-resolution seismic images of older section near the sea floor have been obtained as well. Many of these seismic studies of glacial history have tended to be regional in scale, i.e., they cover many 100s of kilometers with coarsely spaced lines. For example, the ANTOSTRAT project (1995) and other similar studies focused on establishing a regional-scale seismic stratigraphic framework for the entire Ross Sea via correlations to DSDP/ODP and other near-shore drill sites. In the Ross Sea, the ANTOSTRAT project defined six major unconformities (RSU1 through RSU6) within the entire stratigraphic section overlying acoustic basement. These major subdivisions have been related to other phenomena noted from eustatic and composite oxygen-isotope records. Rather than indicating only six major ice-sheet expansions, the stratigraphic intervals delimited by these Ross Sea Unconformities (RSUs) show that multiple cycles of advance and retreat occurred throughout the Cenozoic (e.g., Anderson and Bartek, 1992; DeSantis et al, 1995; Bart, 2003). Since the ANTOSTRAT project, investigators have focused on resolving additional details of the cyrosphere's evolution and its relationship to other phenomena in and outside of the Antarctic at both regional and sub-regional scales.

High-resolution seismic refers to the ability of the seismic instruments used to resolve closely-spaced geologic surfaces with discrete seismic reflections. A high-resolution seismic survey typically involves a single seismic source and a short single-channel-receiver cable to record seismic reflections. The PD88 single-channel-seismic (SCS) grid, acquired in 1988 aboard the Polar Duke R/V on the Antarctic Peninsula by John Anderson's Rice University group, used a small sound source, a 100 cubic inch water gun. The PD90 seismic data grid was regional surveys across the Ross Sea acquired with a 100 cubic-inch generator-injector (GI) air gun as the sound source. Both surveys employed a single-channel streamer to record the seismic reflections measured in two-way travel time. Both of these grids are typical of regional surveys in that spacing between adjacent lines is coarse. For example, on the PD88 grid, the average spacing between adjacent dip lines is ~15 kilometers. The PD88 data contains 3800 km of SCS reflection. Although line spacing is coarse, the spacing is adequate to discern glacial troughs at the scale observed at the seafloor. Thus, these surveys specifications are sufficient to establish a regional seismic-stratigraphic framework.

To seismically image deeper subsurface sections, large-volume seismic air- or water-gun sources are utilized. These higher-volume sources produce a larger outgoing wavelet that has less ability to resolve closely-spaced geologic surfaces. The larger-volume seismic sources generate sound waves that travel longer distances before attenuating.

Given the longer distances over which usable signal travels, these surveys typically use a longer recording cable with multiple receivers (as opposed to single receivers) to record seismic reflections generated at subsurface horizons. In contrast to the single-channel-seismic (SCS) surveys, multi-channel-seismic (MCS) acquisition design has the advantage that it generates multiple seismic traces with a single shot of the seismic source. Thus, while underway on a seismic transect, a single subsurface point is imaged by multiple seismic source-receiver configurations. A major advantage of the MCS design is that it permits the water-bottom multiple (an unwanted reverberation associated with sound reflections in the water column) to be processed out of the seismic data while leaving real subsurface reflections intact.

Antarctic seismic survey parameters

There are limitations to acquiring seismic data in ice-covered waters. Most important among these are the length of the streamer, the tow depth and the configuration of the source and receivers that can be towed behind the ship. The following pertains to SCS surveys. The length of the single channel streamer used in the PD 88 and 90 grids was ~300 meters. Heavy sea-ice conditions during the 1988 survey precluded MCS acquisition. Some of the profiles were acquired while the ship was maneuvering through the sea ice with the water gun or air gun towed directly in the wake of the ship and with large amounts of engine noise and turbulence. This resulted in large amounts of water column noise and gaps in some records. Source and receiver tow-depths varied between one to three meters below the sea surface, depending on sea state and sea-ice conditions. Seismic shot spacing, the distance between adjacent seismic traces, is typically 20 meters. The data are recorded digitally at a 1-millisecond sample rate. Low and high frequency cut-off values for analog data are typically 30 to 800 Hz respectively. Dominant frequency of high-resolution seismic data is between 130 and 200 HZ, providing maximum stratigraphic resolution of 2.5 to 4 meters, based on Rayleigh resolution limit criteria and assuming an average sediment velocity equal to 2000 m/s. Most profiles show a 30- to 60-millisecond seabed reflection consisting of three to six oscillations. Subsurface reflections do not appear to be composed a similar number of oscillations and, at most have a thickness of 20 milliseconds. For those wide reflectors, this is equivalent to an actual stratigraphic resolution of approximately 20 m (assuming a sediment velocity equal to 2000m/s). Seismic data are processed for water-bottom multiple suppression, wavelet filtering and frequency filtering. Wavelet suppression and water-bottom-multiple deconvolution (suppression of the water-bottom reverberations) are part of the typical post-acquisition geophysical processing steps. Seismic reflections on the Antarctic margins commonly exhibit very slight relief over large distances. The broad scale and low relief of the subsurface seismic unconformities is similar to glacial topography existing at the sea floor. At low vertical exaggeration (e.g., 5:1), large-scale, low relief features are difficult to detect. To aid the interpretation, seismic profiles are usually plotted at various vertical exaggerations ranging from 10:1 to 60:1.

Seismic-based criteria for interpretation of glaciogenic features

On the basis of seismic-based criteria outlined in previous studies (e.g., Alonzo et al., 1992; Bart and Anderson, 1996; Bart et al., 2000), seismic reflections exhibiting topset geometry, foreset truncation, regional extent (several tens of kilometers) and cross-cutting relationships between underlying and overlying units are interpreted as unconformities eroded by grounded ice (i.e., ice in contact with the seafloor). Chaotic seismic facies and/or truncated foreset reflections directly below these unconformities are interpreted as proglacial strata that were truncated as the ice sheet advanced across the continental shelf. Prograding low-angle foresets (i.e., till deltas) downlap and partially fill palaeo-troughs formed during prior glacial advances. The absence of seismic evidence of back stepping stratal patterns suggests that ice-sheet retreat from the outer continental shelf was rapid. Thus, seismic reflections interpreted as glacial unconformities presumably correspond to sharp contacts between glacial-phase grounding-zone-proximal sediments (i.e., till) overlain by interglacial pelagic sediments (i.e., diatomaceous ooze) accumulated after ice-sheet decoupling and rapid retreat (Bart and Anderson, 1996; Anderson, 1999).

These seismic-facies interpretations are supported by high-resolution seismic data (chirp and minisparker), swath bathymetry and piston cores from the youngest deposits, which record the LGM advance/retreat of the Antarctic Ice Sheets and subsequent interglacial (e.g., Shipp et al., 1999; Domack et al., 1999). It has also been shown to be applicable for pre-Quaternary ice-sheet grounding events on the Antarctic Peninsula via detailed correlations between seismic and drill site data (e.g., DeSantis et al., 1995; Bart et al., 2005).

Seismic reflections correlated to crossing seismic profiles permit the interpreter to develop a regional seismic stratigraphic framework. In addition, if a sufficiently dense grid of seismic profiles is available, the “3-D” subsurface geometry of the reflection can be determined. The elevations of the seismic reflections measured in two-way travel time are posted on a seismic base map at the locations from which the elevations were recorded. From this posting of subsurface elevations, the interpreter can create a subsurface contour map of the seismic reflection. More and more interpreters are using digital seismic-interpretation workstations for large surveys with closely-spaced seismic lines (e.g., Henrys et al., in press; Descari et al., in press).

One test of a glacial-unconformity interpretation involves determining if the seismic reflectors exhibit glacial-trough and -bank topography. However, at a detailed scale of individual seismic reflections, cross-cutting stratal relationships associated with subglacial erosion are common. Subsurface contour mapping at many stratigraphic levels often shows that dimensions of many seismic reflectors are too small to map large-scale trough and bank topography evident at the seafloor (e.g., Bart et al., 2005). 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 sometimes too widely separated and extents too limited to determine if trough-like features extended across the continental shelf. Nonetheless, the patchy distribution of seismic reflectors at an outer-continental-shelf location is important because it requires that sedimentation was interrupted by seafloor erosion on multiple occasions. The large amounts of erosion make it unlikely that the seismic reflectors resulted from erosive processes involving winnowing by marine currents because the lag produced from clast-rich sediments (known from drill sites on the outer shelves) would have armored the seafloor against substantial erosion before the observed down cutting was accomplished. It is also unlikely that the outer continental shelf 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.

Antarctic-margin clinoform geometries

On the Antarctic outer continental shelves, two types of seismic-stratal units are recognized: 1) aggrading-shelf units and 2) prograding-slope units (e.g., Cooper et al., 1991; Bartek et al., 1991; Bart and Anderson, 1995). The latter features are referred to as Trough Mouth Fans (TMFs) as described by Vorren and Laberg (1997) for similar features in the northern hemisphere. Bart and Anderson (1995) proposed that prograding-slope units were formed during relatively long-duration glacials because they assumed that the magnitude of slope progradation was directly proportional to the duration of ice-sheet grounding at the shelf edge. In an alternate interpretation of margin evolution, Rebesco et al. (1998) propose that upper-slope progradation occurs on those sectors of the margin where ice was not streaming. In this line of reasoning, sediment debouching from ice streams were sufficiently fluidized that it moved down the continental slope as dilute sediment gravity flows to a continental-rise depocenter.

As the name implies, TMFs are upper-slope fans of sediment that occur at the mouth of a glacial trough. In the Antarctic, the Crary TMF is manifest as a prominent basinward deflection in the outer shelf and upper slope (Moons et al., 1992). In Northern Basin, Ross Sea, the Joides TMF occupies a re-entrant in the shelf-edge trend (Bart et al., 2000). On the Antarctic Peninsula's pacific margin, large troughs cross the margin, but sinuous trend of the shelf edge is a relict from an earlier interval of TMF development pre-dating the Pleistocene followed by an interval during which the margin aggraded.

Both aggradational and progradational types of seismic units are bound by seismic reflections that exhibit topset geometry with basinward tilt (due to higher subsidence on the outer shelf and/or uplift on the middle shelf). Aggrading-shelf units display minimal slope progradation (< 2 to 3 km) beyond the pre-existing shelf edge. Units of this type are composed of either acoustically layered low-angle prograding foresets (in rare instances) or acoustically-chaotic seismic facies. Unit thicknesses vary along the shelf from less than 20 milliseconds (msec) two-way travel time (~15 m) to more than 200 msec (~150 m). Prograding-slope units exhibit local slope progradation in excess of 2 to 3 km beyond the location of the pre-existing shelf edge.

Lithologic and chronologic control on seismic-based interpretation of the Antarctic outer continental shelf

As noted earlier, piston-core based studies provide materials that permit a measure of lithologic and chronologic control for LGM and post-LGM reconstructions. Ground-truth for pre-LGM reconstructions for the outer continental shelf relies on the relatively few DSDP and ODP sites (e.g., DSDP/ODP Legs 28, 35, 119, 178, 188). An equally small number of near-shore sites have been drilled, primarily in Ross Sea near McMurdo station (e.g., CIROS, Dry Valleys Drilling Project, Cape Roberts Project, ANDRILL). On the outer continental shelves, drill sites have had low recovery. At ODP Leg 178 Site 1097, the depth interval from core segments 23R to 51R has recovery of 16.7%. Forty-two measurements of sediment velocity were made at Site 1097. Since the velocity structure at the site is somewhat poorly known, the conversion of two-way travel time to core depth is poorly resolved. In a detailed correlation between seismic reflectors and lithologic control at ODP Leg 178 Site 1097, Bart et al. (2005) found that units bound by seismic reflectors interpreted as glacial unconformities indeed contained subglacial sediments as interpreted by Eyles et al. (2001). According to Bart et al. (2005), the up-core lithologic changes at Site 1097 (from glaciomarine sections at their bases to subglacial sections at their tops) are consistent with the general view of deposition and erosion from an advancing ice sheet at several stratigraphic levels.

Seismic reflectors are also correlated to age control (usually based on diatom biozones). Diatom biozones described by Winter and Iwai (2002) at ODP Leg 178 Site 1095 were used to constrain the timing of ice sheet grounding events deduced from seismic stratigraphy. Seismic correlations to diatom biozones indicate that as many as 12 grounding

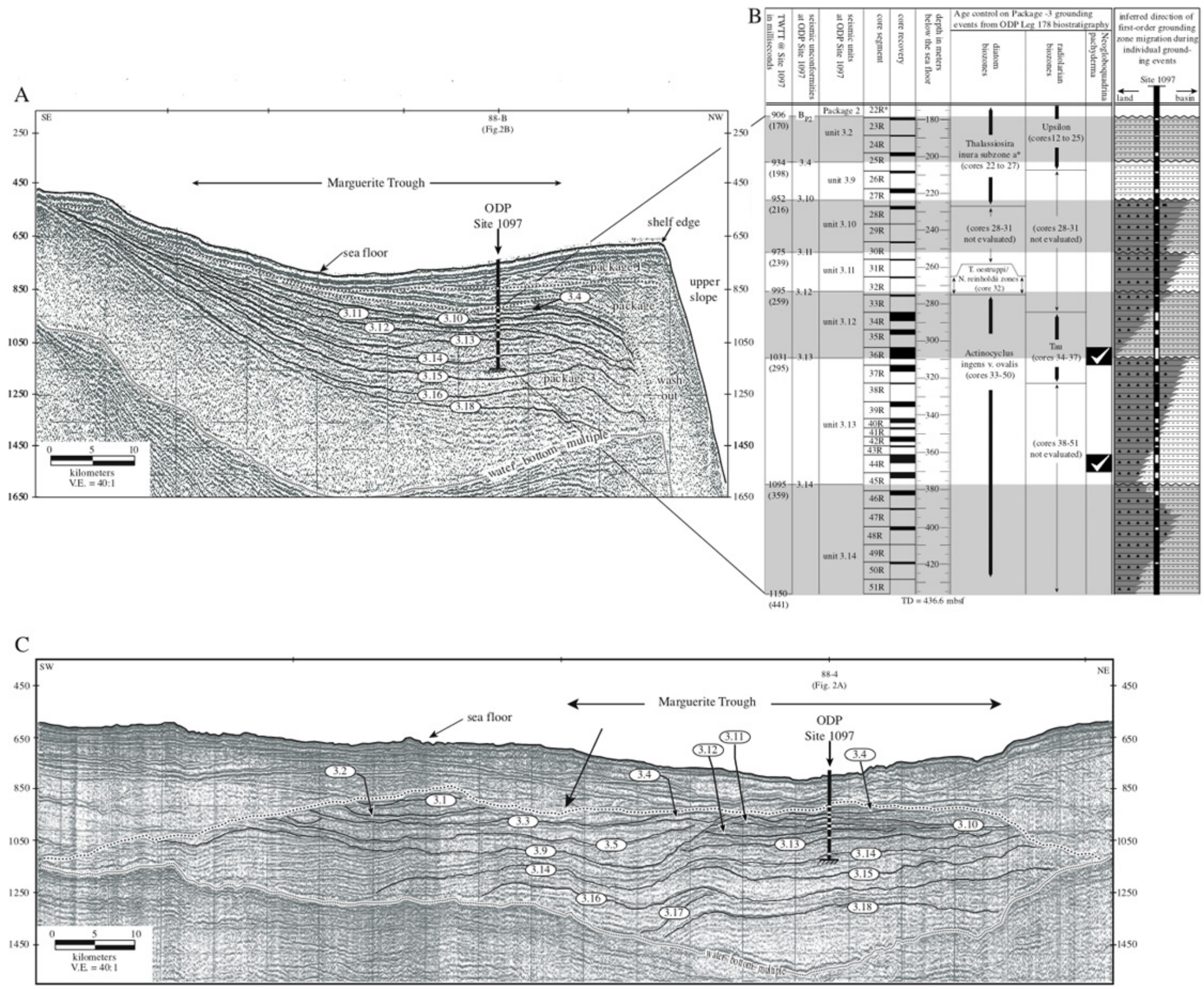

Figure 1. Seismic lines and ODP Leg 178 Site 1097 information from the pacific margin of the Antarctic Peninsula. A) Dip-oriented PD88-4. Black lines correspond to reflections interpreted as glacial unconformities within a section referred to as Package 3 by Bart et al. (2005). These surfaces were eroded by the Antarctic Peninsula Ice Sheet. In contrast to the aggrading clinoforms within Package 3 (and Package 1), Package 2 exhibits an overall progradational form typical of Trough Mouth Fans. B) Strike-oriented profile PD88-B. In strike-view, the numerous cross cutting relationships produce a very patchy distribution for any one surface and unit on the outer continental shelf. The cross-cutting suggests that the position of ice streams shifted during successive ice-sheet advances. C) ODP Leg 178 drill site lithologic information from Eyles et al. (2001) and diatom biozones (Winter and Iwai, 2002) confirm that multiple ice sheet advances occurred within the latest Miocene and earliest Pliocene. The inferred direction of grounding zone locations (upper right part of Figure 1C) is based on the up-core lithologic changes. Dark gray with black triangles corresponds to subglacial sediments and dashed zones correspond to glacial marine section. The recovery is indicated by white lines within the vertical heavy black line (from Bart et al., 2005)

events occurred on the pacific margin of the Antarctic Peninsula during an ~3 Ma interval of the latest Miocene/earliest Pliocene (Bart et al., 2005). Dip-oriented seismic profile PD88-4 and strike-line profile PD88-B (Figures 1a and 1b, respectively) from the Antarctic Peninsula's pacific margin show correlations of seismic reflections interpreted as glacial unconformities from the outer continental shelf at Marguerite Trough. Both seismic lines intersect at the location of ODP Leg 178 Site 1097 and thus lithologic and chronologic control (based on diatom biozones) are available to confirm the glacial interpretation at this location (Figure 1c). Elsewhere, on the Ross Sea outer continental shelf, the overall seismic stratigraphic signature of the Neogene section is generally consistent with the sequence stratigraphic signature from other low-latitude continental margins (Bartek et al., 1991). This and other studies strongly suggest that genetic links do indeed exist between sequence boundaries and major glacial unconformities on

Antarctica's outer continental shelf. The challenge remains to more precisely constrain the age of individual grounding events (as indicated from regional seismic studies of the Antarctic margins) in a way that would permit direct correlations to other climatic/eustatic phenomena detected elsewhere on the continent and at low latitudes.

References

Alonso, B., Anderson, J.B., Diaz, J.T., and Bartek, L.R., 1992, Plio-Pleistocene seismic stratigraphy of the Ross Sea: Evidence for multiple ice sheet grounding episodes, in Elliot, D.H., ed., Contributions to Antarctic research III: Antarctic Research Series, v. 57, p. 93-103.

Anderson, J.B., 1999. Antarctic Marine Geology, Cambridge University Press, Cambridge.

Anderson, J.B., Bartek, L.R., 1992. Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information. Antarctic Research Series, 56 (The Antarctic Paleoenvironment: A perspective on global change) (1992) 231-263.

ANTOSTRAT (Antarctic Offshore Stratigraphy 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.

Barrett, P. J., 1996. Antarctic paleoenvironment through Cenozoic times: a review. Terra Antart., 3, 103-119.

Bart, P.J., Anderson, J.B., 1995. Seismic record of glacial events affecting the Pacific margin of the northwestern Antarctic Peninsula. In: Cooper, A.K., Barker, P.F., Brancolini, G. (Eds.), Geology and Seismic Stratigraphy of the Antarctic Margin. Antarctic Research Series, Washington D.C. , American Geophysical Union, 68, 75-95.

Bart, P.J., Egan, D.E., Warny, S.A., 2005. Direct constraints on Antarctic Peninsula Ice Sheet grounding events between 5.12 and 7.94 Ma. Journal of Geophysical Research, 110, F04008.

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.

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.

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.

Decesari, R.C., Sorlien, C.C., Luyedyk, B.P., Wilson, D.S., Bartek, L.R., Diebold, J. and Hopkins, S.E., in press, Regional seismic stratigraphic correlations of the Ross Sea; implications for the tectonic history of the West Antarctic Rift System, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A. K. Cooper and Raymond C.R. et al., USGS Open-File Report 2007.

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.

Eyles, N., Daniels, J., Osterman, L.E., Januszcak, N., 2001. Ocean Drilling Program Leg 178 (Antarctic Peninsula): sedimentology of glacially influenced continental margin topsets and foresets. Marine Geology, 178, 135-156.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science, 235, 1156-1167.

Henrys, S. A., T. J. Wilson, J. M. Whittaker, C. R. Fielding, J. M. Hall and T. Naish, in press, Tectonic History of Mid-Miocene to Present Southern Victoria Land Basin, inferred from Seismic Stratigraphy, in McMurdo Sound, Antarctica, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A. K. Cooper and Raymond C.R. et al., USGS Open-File Report 2007.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005, The Phanerozoic record of global sea-level change. Science 310, 1293-1298.

Mitchum, R.M., Jr., Sangree, J.B., Vail, P.R., Wornardt, W.W., 1994. Recognizing sequences and systems tracts from well logs, seismic data, and biostratigraphy; examples from the late Cenozoic of the Gulf of Mexico. American Association of Petroleum Geologists, 58, 163-197.

Moons, A., De Batist, M., Henriet, J.P. and Miller, H., 1992, Sequence Stratigraphy of Crary Fan Southeastern Weddell Sea, Yoshida, Y., Kaminuma, K., and Shiraishi, K., eds., Recent Progress in Antarctic Earth Science: Tokyo, Terra Scientific Publishing Company, p. 613-618.

Rebesco, M., Camerlenghi, A., Zanolla, C. 1998. Bathymetry and morphogenesis of the continental margin west of the Antarctic Peninsula. Terra Antart., 5, 715-728.

Shackleton, N.J., Kennett, J.P., 1975. Paleotemperature history of the Cainozoic and the initiation of Antarctic glaciation: oxygen and carbon analysis in DSDP sites 277, 279 and 281. Initial reports of the Deep Sea Drilling Project, 29, 743-755.

Shackleton, N.J., Opdyke, N.D., 1976. Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239 late Pliocene to latest Pleistocene. In: Cline, R.M. and Hays J. (Eds.), Investigation of late Quaternary paleoceanography and paleoclimatology. Geological Society of America Memoir, 145, 449-464.

Shackleton, N. J., Hall, M. A., 1984. Oxygen and carbon isotope stratigraphy of Deep Sea Drilling Project Hole 552A: Plio-Pleistocene glacial history. In: Roberts, D.G., Schnitker, D., et al. (Eds.), Initial reports of the Deep Sea Drilling Project, United State Government Printing Office, Washington, D.C., 81, 599-609.

Vorren, T.O. and Laberg, J.S., 1997, Trough mouth fans – palaeoclimate and ice-sheet montors: Quaternary Science Reviews, v. 16, p. 865-881.

Shipp, S., Anderson, J.B., Domack, E.W., (1999) Seismic signature of the Late Pleistocene fluctuation of the West Antarctic Ice Sheet. GSA Bulletin. 111 1486-1516.

Winter, d. and M. Iwai (2002), Data Report: Neogene Diatom Biostratigraphy, Antarctic Peninsula Pacific Margin, ODP Leg 178 Rise Sites. In: Barker, P.F., Camerlenghi, A., Acton, G.D., and Ramsay, A.T.S. (Eds.), Proc. ODP, Sci. Results, 178, 1-25 [CD-ROM].

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686-693.