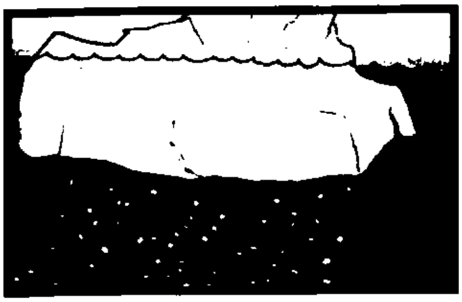

ODP Drilling Leads to a New Model of Shelf and Slope Sedimentation along the Antarctic Continental Margin

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SUMMARY

Three recent Ocean Drilling Program (ODP) cruises — Leg 178, Antarctic Peninsula; Legs 119 and 188, Prydz Bay — have drilled various parts of the Antarctic continental margin in an effort to constrain the history of the Antarctic Ice Sheet. Integration of geophysical, biofacies, and sedimentological data from these ODP legs suggests that a very similar style of continental margin growth has occurred along the Antarctic continental margin. Data from the Antarctic continental margin suggest that the shelf aggrades ("upbuilds") during periods of ice front retreat, whereas the slope progrades ("outbuilds") during episodes of ice advance to the shelf break. Because other glaciated continental margins have glacial marine successions similar to that of the Antarctic continental margin, it may be that a common or "unified" model of glaciated margin deposition exists, regardless of latitude and geological age.

RÉSUMÉ

Lors de trois campagnes récentes du Programme de sondage des fonds marins (PSFM) — le segment 178, péninsule de l'Antarctique; les segments 119 et 188, baie de Prydz — diverses portions de la marge continentale de l'Antarctique ont été sondées par forage dans le but de mieux définir l'histoire de l'inlandsis antarctique. L'intégration des données géophysiques, de biofaciès et sédimentologiques récoltées lors de ces campagnes du PSFM donne à penser qu'un style très semblable de croissance de la marge continentale s'est produit tout du long de la marge continentale de l'Antarctique. Les données de la marge continentale antarctique semblent montrer qu'il y a aggradation (épaississement du dépôt) durant les périodes de retrait du front glaciaire, alors qu'il y a progradation (étalement du dépôt) durant les périodes d'avancée du front glaciaire vers le rebord de la plate-forme continentale. Étant donné que d'autres marges continentales englacées montrent des empilements sédimentaires glacio-marins semblables à ceux de la marge continentale antarctique, il se pourrait bien qu'un seul modèle sédimentaire des marges continentales glaciaires suffise, quels que soit la latitude et l'âge géologique.

INTRODUCTION

Although the Antarctic Ice Sheet is a key component of the world's climate system and has a major influence on global sea levels, the Cenozoic history of the ice sheet and its depositional history are poorly constrained. Attempts have been made to reconstruct the history of the ice sheet over the last 40 m.y. using indirect proxy data, such as oxygen isotope data (Miller *et al.*, 1987; Shackleton and Kennett, 1975), sea level onlap/offlap curves (Haq *et al.*, 1987), and the record of ice-rafting from the southern oceans (Ehrmann, 1991). These methods have had limited, and often contradicting, results, owing to the influence of Northern Hemisphere ice sheets on oxygen isotope data and the questionable validity of global sea level curves and inferred glacioeustatic fluctuations (*e.g.*, Burton *et al.*, 1987; Miall, 1986; Underhill, 1991). For the Antarctic setting, establishing a detailed history of ice-sheet growth and decay depends on drilling the sedimentary record of the Antarctic continental margin and achieving an understanding of how the ice sheet behaves in response to changes in the adjoining ocean. Estimates of the volume of glacially eroded sediments delivered to the Antarctic continental margin during different phases of the continent's history is a significant factor in modelling ice sheet behaviour through time.

Current understanding of the evolution of the Antarctic continental margin is based on more than 30 years of scientific study in the region. Seismic reflection techniques provided the first regional view of the subsurface and the stratal geometry of the margin. Sedimentological ground-truthing data was provided by drilling programs that began in earnest in 1972, when Deep Sea Drilling Project (DSDP) Leg 28 drilled four holes in the western Ross Sea continental shelf (Hayes and Frakes, 1975). Seismic profiles of the Antarctic continental margin reveal a glaciated shelf with large-scale, flat-lying topset strata recording aggradation ("upbuilding") of the shelf, and underlying, seaward-dipping foreset strata recording progradation ("outbuilding") of the slope (Fig. 1). These prograding foresets and aggrading topsets are thought to record advances and retreats of the ice sheet (ice front retreats), respectively.

To address the need to further ground-truth a substantial seismic dataset, the Antarctic Offshore Stratigraphy Project (ANTOSTRAT) fostered a series of Antarctic drilling proposals. Each proposal was designed to address different aspects of Antarctic glacial history. ODP Leg 178 (Fig. 2B) examined the glacial history of the Antarctic Peninsula, which is covered by small ice masses that developed during the Neogene and respond rapidly to climate changes (Barker *et al.*, 1999). ODP Leg 188 (Fig. 2C), drilled in Prydz Bay seaward of the Amery Ice Shelf, was designed to address the history of the East Antarctic Ice Sheet, which is long lived and responds relatively slowly to major climatic events (O'Brien *et al.*, 2001; O'Brien *et al.*, 1999). Prydz Bay was previously drilled by ODP in 1988 (Leg 119, Fig. 2C; Cooper *et al.*, 1991; Barron *et al.*, 1991). ODP Leg 188 results, in conjunction with those from Leg 119, provide insights into the dynamics of the East Antarctic Ice Sheet.

The following sections outline results from these three recent ODP drilling legs along the Antarctic continental margin (Fig. 2). Similarities in depositional processes and patterns from both settings, the Antarctic Peninsula and

Prydz Bay, suggest that a unified depositional model for the Antarctic continental margin may exist. This model may be applicable to other glaciated continental margins at other latitudes and of other geological ages.

ODP LEG 119, PRYDZ BAY, ANTARCTICA, 1988

The primary objective of drilling in Prydz Bay in 1988 (Fig. 2C) was to obtain the Mesozoic through Holocene climatic and glacial history of Antarctica as recorded in the sediments of the broad and deep Antarctic continental shelf (Barron *et al.*, 1991). An extension of that objective was the need to verify the commonly accepted interpretation of the oxygen isotope record of climate trends current in 1988. An abrupt increase in ^{18}O at the Eocene-Oligocene boundary was thought then to reflect the first formation of Antarctic sea ice and the consequent establishment of cold bottom water. The second abrupt enrichment in the middle Miocene was thought then to reflect the establishment of full Antarctic ice sheet conditions (Shackleton and Kennett, 1975; Kennett, 1978). ODP Leg 113 results (eastern Weddell Sea) were interpreted in the same manner (Barker *et al.*, 1987), but at the time there was no other Antarctic site to corroborate that interpretation.

ODP Leg 119 was one of the earliest investigations (1988) involving deep-drilling of the Antarctic continental margin. Earlier studies by the Deep Sea Drilling Project (DSDP) in sub-Antarctic waters had demonstrated the existence of glacial deposits as old as 25 Ma, which overlie Oligocene glauconite sandstone dated at 26.7 Ma (Hayes and Frakes, 1975). Drilling in the western Ross Sea had extended the record of glacially related deposition back to the early Oligocene (CIROS-1 borehole; see Barrett, 1989): this record is complicated, however, by the proximity of the Transantarctic Mountains, which were uplifted during the Cenozoic to their present elevation of more than 4000 m (Gleadow *et al.*, 1984).

The Antarctic depositional model favoured at the time of Leg 119 was a simple climate-driven model derived from the identification of seismostratigraphic units on the Antarctic Peninsula (*e.g.*, Larter and Barker, 1989). This "climate model" suggests that the margin progrades during ice expansion to the shelf break, and aggrades during ice retreat or interglacials when biogenic deposition — not glacial till — predominates. This model was also supported by the Shipboard Scientific Party on Leg 119 (Hambrey *et al.*, 1991; their fig. 27). Later seismic studies on the Antarctic Peninsula by Bart and Anderson (1995) found that the continental margin did not prograde as a simple 2-D, line-grounding episode as suggested by the climate model, but rather as discrete, 3-D lenses or "tongues" with complex stacking patterns. This suggested that complex sedimentary processes were taking place along the Antarctic continental margin. Insight into these processes was gained during ODP Legs 178 and 188.

ODP LEG 178, ANTARCTIC PENINSULA, 1998

Ocean Drilling Program Leg 178 drilled the Pacific-facing margin of the Antarctic Peninsula from February to April 1998 (Fig. 2B). The objectives included obtaining a high-resolution record of continental glaciation from topset and foreset beds drilled on the continental shelf and slope. Before this could be accomplished, however, the main controls on sediment transport and deposition along the margin had to be identified. Eyles *et al.*, (2001) used lithofacies and biofacies data from two sites on the continental shelf, Sites 1097 and 1103 (Figs. 3, 4; site locations in Fig. 2B), to improve current understanding of depositional processes leading to the formation of glaciated continental margin topsets and foresets in Antarctica.

Sedimentological and biofacies data from the shelf site, Site 1097, contradicted the simple, 2-D climate model for margin growth which suggested that the Antarctic Peninsula continental shelf aggrades during interglacials, and that the slope progrades only during major glaciations (Larter and Barker, 1989; Larter and Cunningham, 1993). Data from Site 1097A demonstrated that topsets are composed of substantial thicknesses of poorly sorted diamictite (till) deposited during shelf-wide glaciation (Fig. 4; Eyles *et al.*, 2001). The earlier (1995) detailed seismic investigation of the Antarctic Peninsula continental shelf and slope, presented by Bart and Anderson (1995), used both dip and

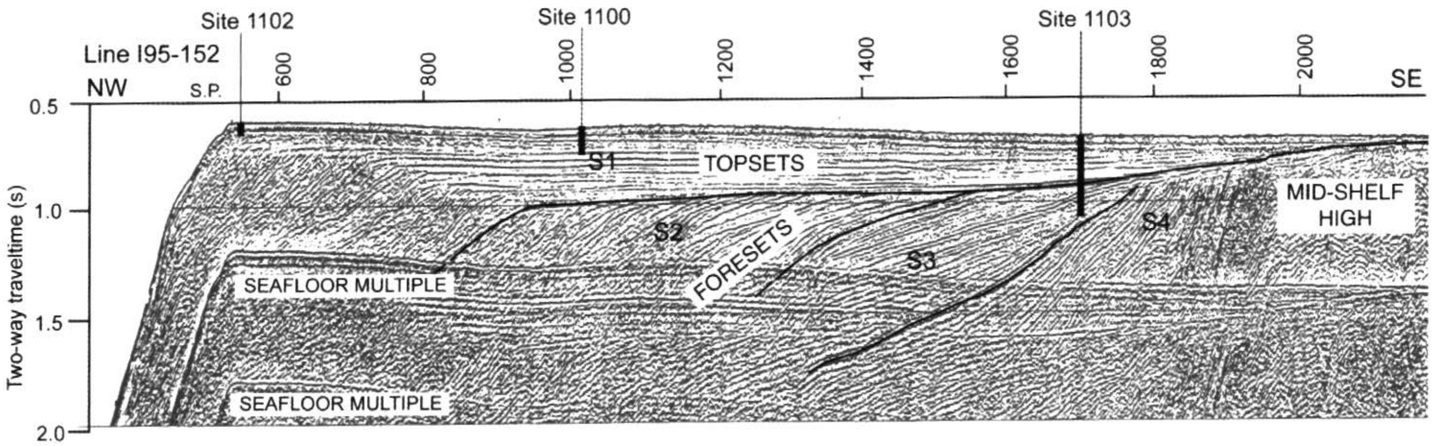


Figure 1 Acoustic stratigraphy of the Antarctic Peninsula Pacific-facing continental margin (ODP Leg 178) showing flat-lying topset reflectors and underlying steeply dipping foreset reflectors. Seismo-stratigraphic units S1 (topset) and S2,3 (foresets) are from Barker *et al.* (1998). Seafloor multiples identified obscure seismic stratigraphy at deeper levels.

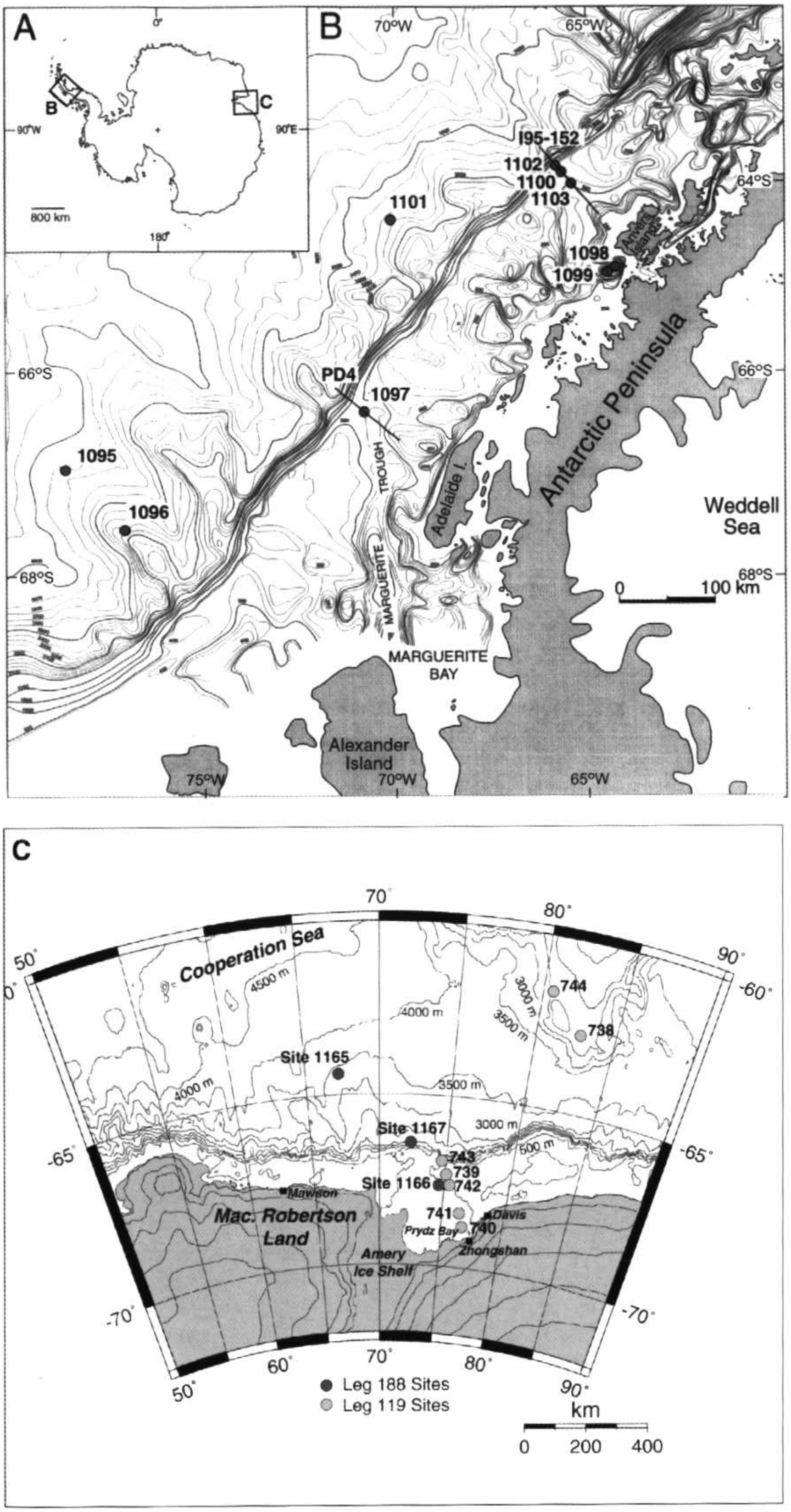


Figure 2 (**A**) General location map of recent ODP drilling in Antarctica; (**B**) Location of ODP Leg 178 drill sites along the Antarctic Peninsula Pacific margin (Barker *et al.*, 1999); (**C**) Location of ODP Legs 119 and 188 drill sites in Prydz Bay (O'Brien *et al.*, 2001).

strike profiles, and shows both multiple unconformities within topset successions, and considerable along-strike variation in the geometry of the foresets. Bart and Anderson (1995) suggested that chaotic seismic facies are tills, and this conclusion was supported by lithofacies and biofacies data from topsets at Site 1097A (Fig. 4).

The lower section of the sedimentary record at Site 1103A provided insight into the fate of sediments at the shelf edge, where slope foresets prograde by the reworking of glacial debris (till) and marine sediments as debris flows and turbidity currents (Figs. 3, 4; Eyles *et al.*, 2001). The preservation of hemipelagic sediments within slope foreset stratigraphy suggests that the slope offers an attractive target for a high-resolution record of climatic and oceanographic change (Eyles *et al.*, 2001).

ODP LEG 188, PRYDZ BAY, ANTARCTICA, 2000

From January to March 2000, Ocean Drilling Program Leg 188 drilled a transect of three sites roughly perpendicular to the Prydz Bay continental margin (Fig. 2C): one on the continental shelf (Site 1166); one on the continental slope (Site 1167 in the Prydz Channel Trough Mouth Fan); and one on a sediment drift on the continental rise (Site 1165). These sites were selected in order to investigate: 1) Cretaceous pre-glacial conditions, 2) the transition from pre-glacial to glacial conditions in Prydz Bay, and 3) the dynamics of the East Antarctic Ice Sheet in the Cenozoic.

The Lambert Graben-Prydz Bay Basin fill consists of two lower sequences of parallel-bedded units that onlap or are faulted against basement beneath the northwestern and southeastern sides of the basin. These sequences were penetrated at ODP Sites 740 and 741 drilled during Leg 119 in 1988 (Fig. 2C), and consist of Cretaceous coal-bearing nonmarine sediments overlying nonmarine redbeds (Turner and Padley, 1991; Turner, 1991). Cenozoic sequences overlying the Cretaceous were recovered on Leg 188 in 2000, and are composed of temperate Late Eocene alluvial-deltaic sandstones (Unit III, Fig. 5). A transgression at the top of the sandstones is conformably overlain by a Late Eocene proximal glaciomarine (proglacial) succession characterized by interbedded mudstones and sandstones (Unit II, Fig. 5). This proglacial succession is truncated by an erosional unconformity that is overlain by massive diamictite (sub-units ID, IB, Fig. 5). The seismic character of

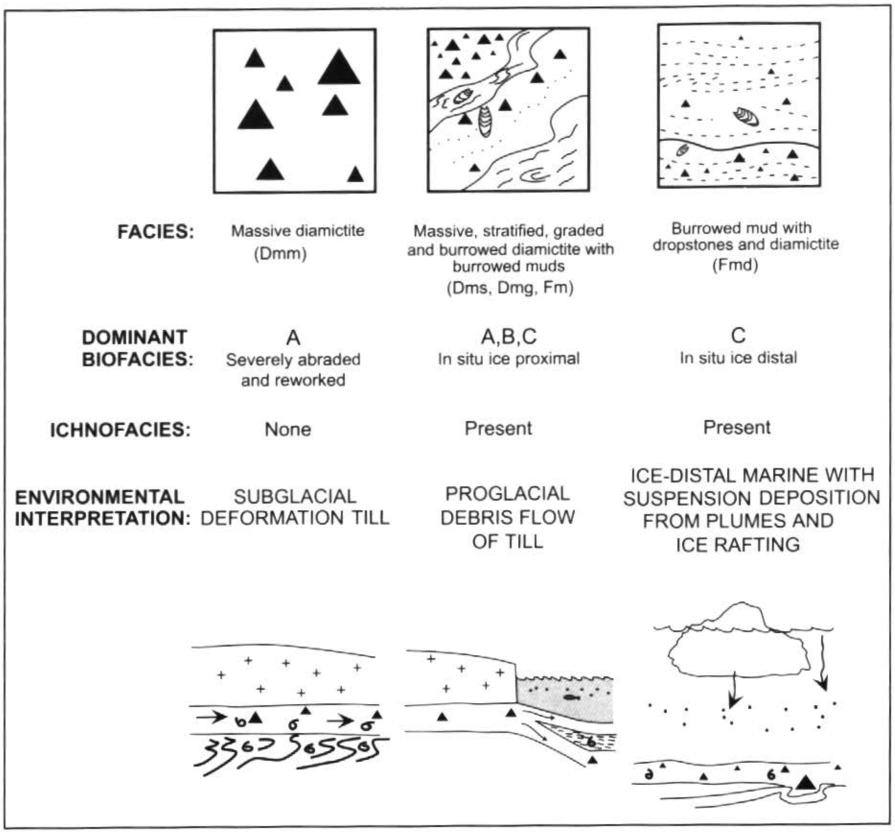
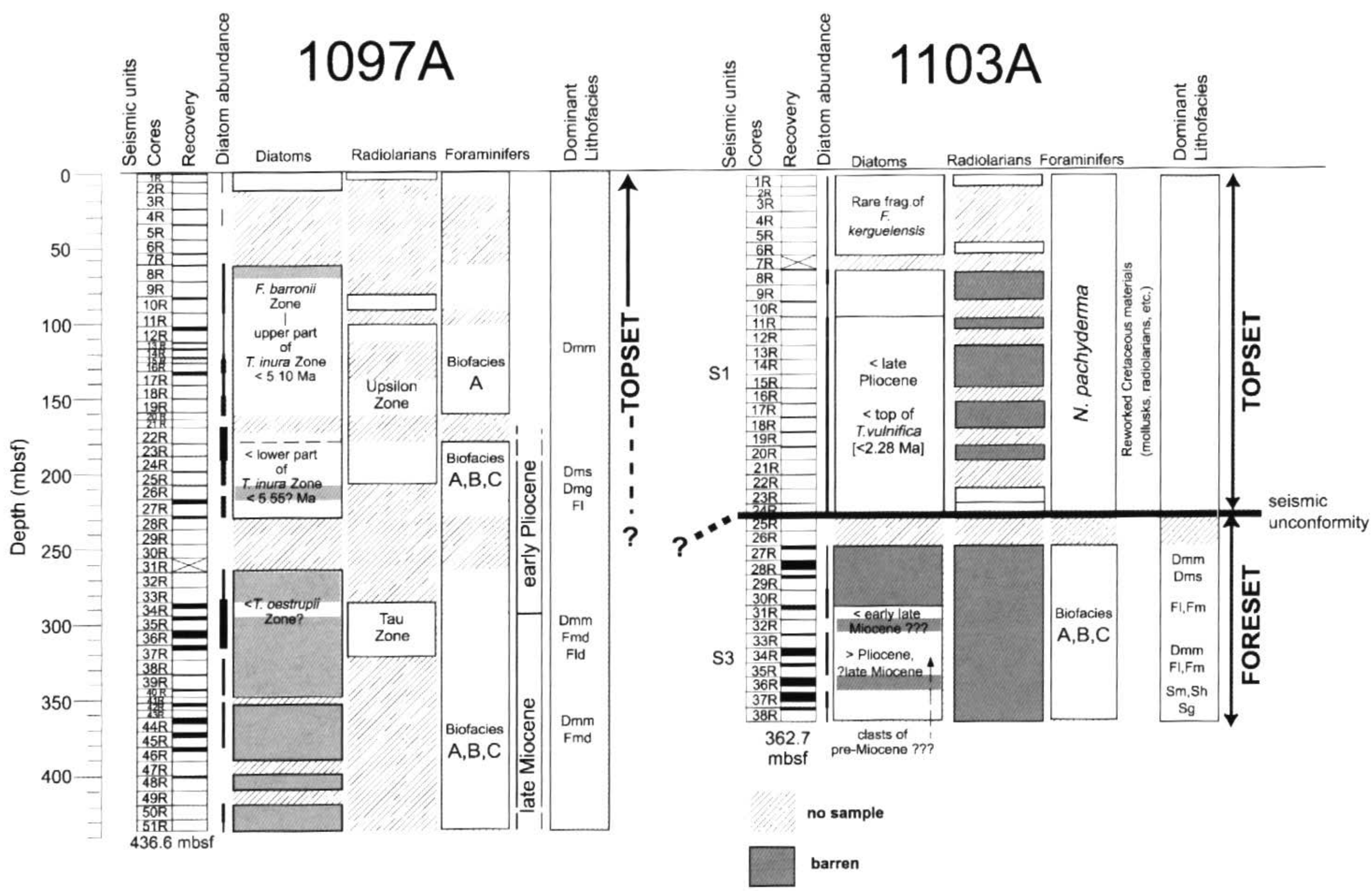


Figure 3 (at right) Environmental interpretation of lithofacies and associated biofacies recovered from ODP Leg 178 (modified from Eyles *et al.*, 2001).

Figure 4 (below) Summary figure for ODP Leg 178 Sites 1097 and 1103 showing core recovery (black) and dominant lithofacies types. Dmm = Diamictite, massive, matrix supported; Dms = Diamictite, stratified; Dmg = Diamictite, graded. Fm = mud, massive; Fmd = mud, massive, with dropstones; Fl = mud, laminated; Fld = mud, laminated, with dropstones. Sm = sand, massive; Sh = sand, horizontally laminated; Sg = sand, graded. Biostratigraphic age control is provided by diatoms and radiolarian assemblages. Facies and biofacies codes are explained and illustrated in Figure 3 (after Eyles *et al.*, 2001).



the unit I diamictites is flat-lying topset beds recording aggradation of the shelf (Fig. 6). Diatoms in a small (< 50 cm) mudstone interval preserved within the massive diamictites are Late Pliocene in age (sub-unit 1C, Fig. 5; O'Brien *et al.*, 2001). Thus the aggraded beds in this setting are diamictite (till), not biogenic deposits as predicted by the earlier climate model (*e.g.*, Larter and Barker, 1989).

During some (but not all) Cenozoic glacial episodes, the Lambert Glacier advanced to various positions on the shelf, and built a large trough mouth fan that records major advances to the shelf break (O'Brien *et al.*, 2001; O'Brien *et al.*, 1999; O'Brien and Harris, 1996). On seismic profiles, the growth of the fan is characterized by prograding foresets that "outbuild" from the shelf break (Fig. 7). Plio-Pleistocene intervals recovered on Leg 188 suggest that interglacial sediments are preserved on the slope foresets within diamictites; thus, the Prydz Channel Fan contains a measure of the

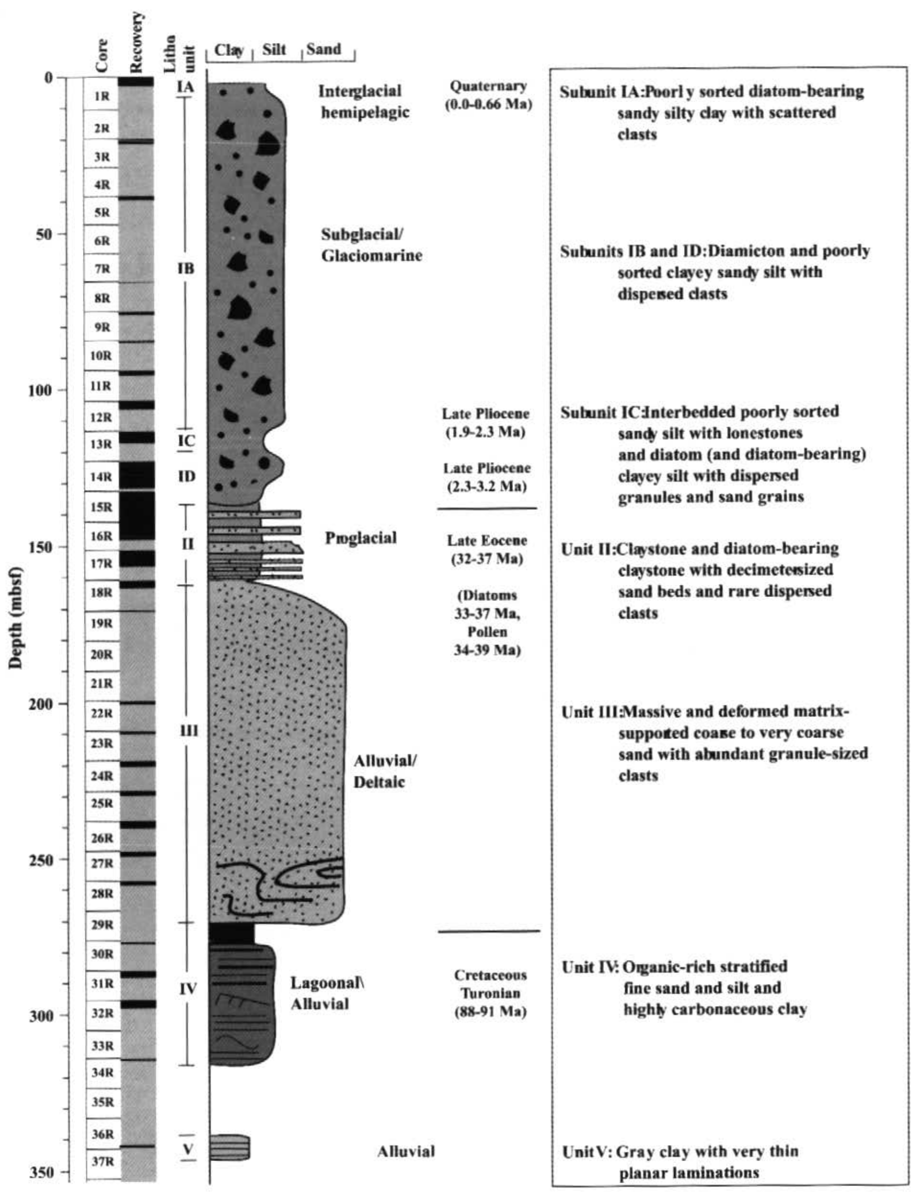


Figure 5 (**at left**) Summary figure for ODP Leg 188, Site 1166, Prydz Bay (location given in Fig. 2C) including core recovery (black), lithostratigraphic units, age, facies descriptions, and environmental interpretation (modified from O'Brien *et al.*, 2001).

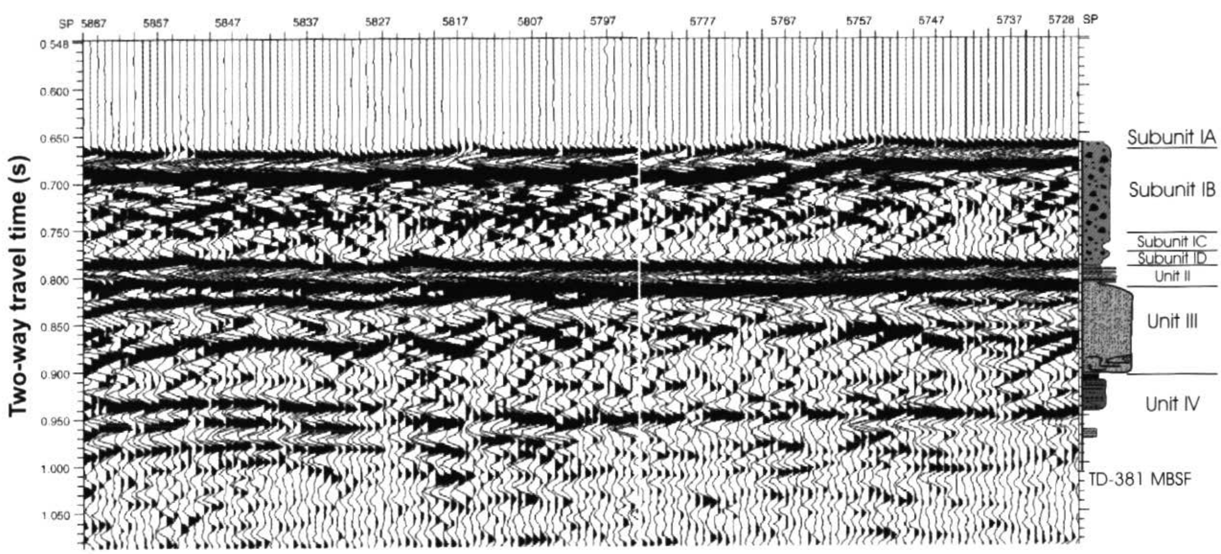


Figure 6 (**below**) Seismic reflection profile from ODP Leg 188, Site 1166, Prydz Bay (location given in Fig. 2C). At Site 1166 the seismic profile is dominated by flat-lying topset reflectors (modified from O'Brien *et al.*, 2001).

major sediment pulses caused by peaks in Antarctic ice volume over the last 4-5 m.y. The sediments that make up the fan are predominantly debris flow facies (*e.g.*, turbidites), and indicate reworking of shelf-derived glaciomarine material downslope during periods of peak ice advance (Fig. 8).

CONCLUSIONS

Recent Antarctic drilling initiatives include those of ANTOSTRAT (Antarctic Offshore Stratigraphy Project; ODP Legs 178 and 188) and CRP (Cape Roberts Project; Ross Sea). Newly derived data from the Antarctic margin, in conjunction with recent studies that have reevaluated earlier work (*e.g.*, Fielding *et al.*, 1997 (CIROS-1)), can now be used to refine existing depositional models of the margin originally based mostly on seismic datasets. The new data suggest that the shelf aggrades ("upbuilds") during periods of ice stagnation or retreat, the record of which is substantial thicknesses of till; and the slope progrades ("outbuilds") with the reworking of glaciomarine material downslope *via* turbidity currents and debris flow events during episodes of ice advancement to the shelf break.

Glacial marine successions similar to those identified on ODP Legs 119, 178 and 188 are reported from many other Pleistocene glacially-influenced continental margins (*e.g.*, Hill, 1984; Vorren *et al.*, 1989; Stoker *et al.*, 1991; Aksu and Hiscott, 1992; King *et al.*, 1998) and also from the pre-Pleistocene record (Visser, 1983; Miall, 1985; Eisbacher, 1985; Young and Gostin, 1991; Eyles, 1993; Eyles and Lagoe, 1998; McB Martin, 1999). A very similar style of continental margin growth has apparently occurred along the southeast Greenland margin (Clausen, 1998), the northwestern Norwegian margin (Saettem *et al.*, 1992) and along the eastern Canadian margin (Hiscott and Aksu, 1994). This large literature suggests that a common or "unified" model of glaciated margin deposition may exist, perhaps irrespective of latitude or geological age. Testing this hypothesis is the aim of current investigations at the University of Toronto.

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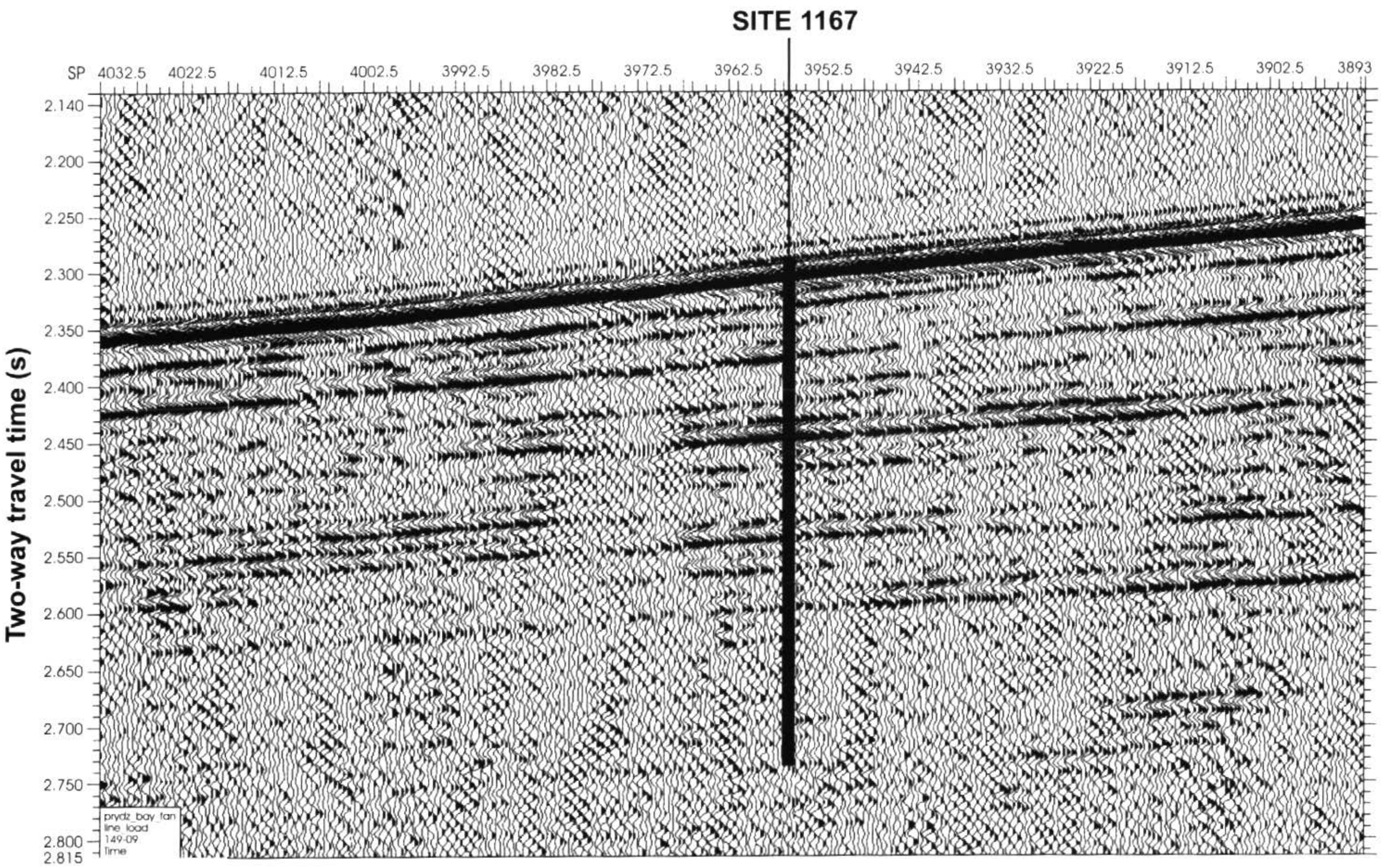

Figure 7 Seismic reflection profile from ODP Leg 188, Site 1167, Prydz Bay (location given in Fig. 2C). At Site 1167 within the Prydz Channel Trough Mouth Fan the reflectors have a regional seaward dip (modified from O'Brien *et al.*, 2001).

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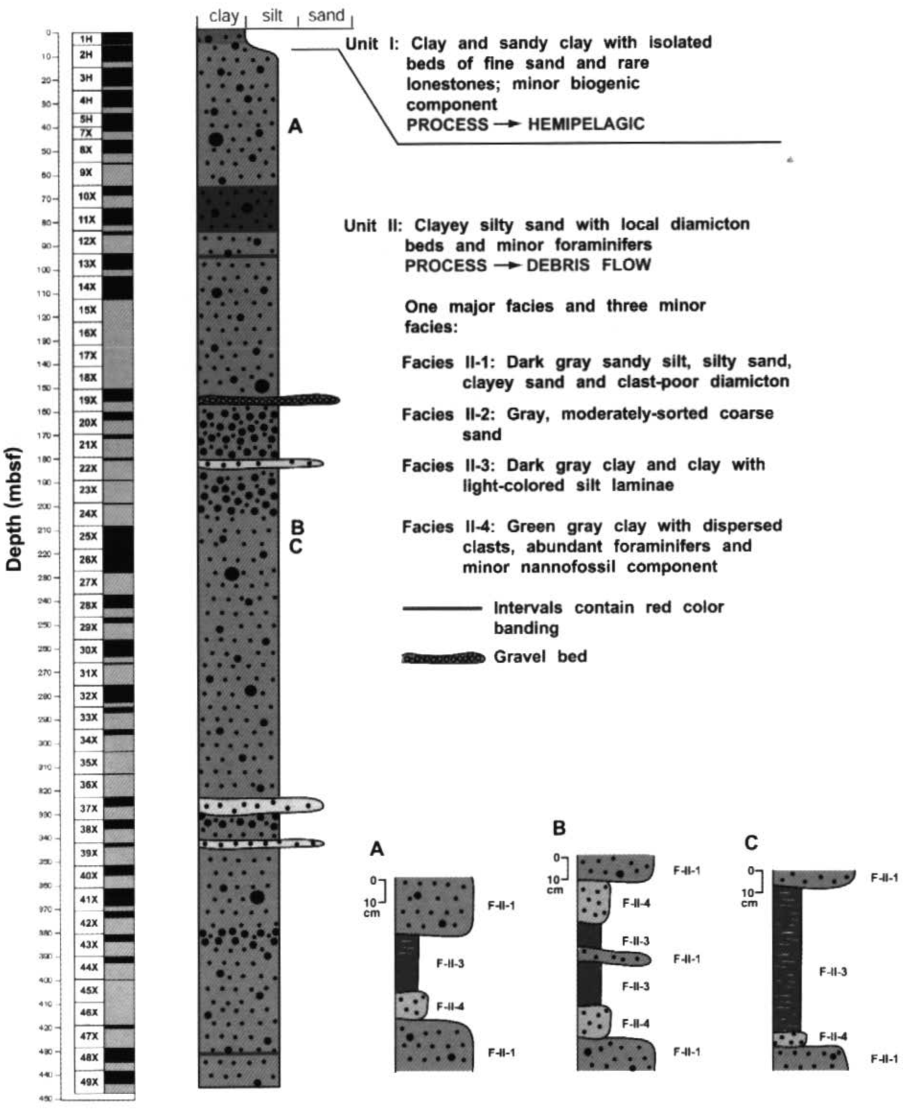

Figure 8 Summary figure for ODP Leg 188, Site 1167, Prydz Bay (location given in Fig. 2C) including core recovery (black), lithostratigraphic units, facies descriptions, and environmental interpretation. Letters A, B, and C on main stratigraphic column are levels at which detailed facies variations occur, as seen in detailed schematic columns A, B, C at base of figure (modified from O'Brien *et al.,* 2001).

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