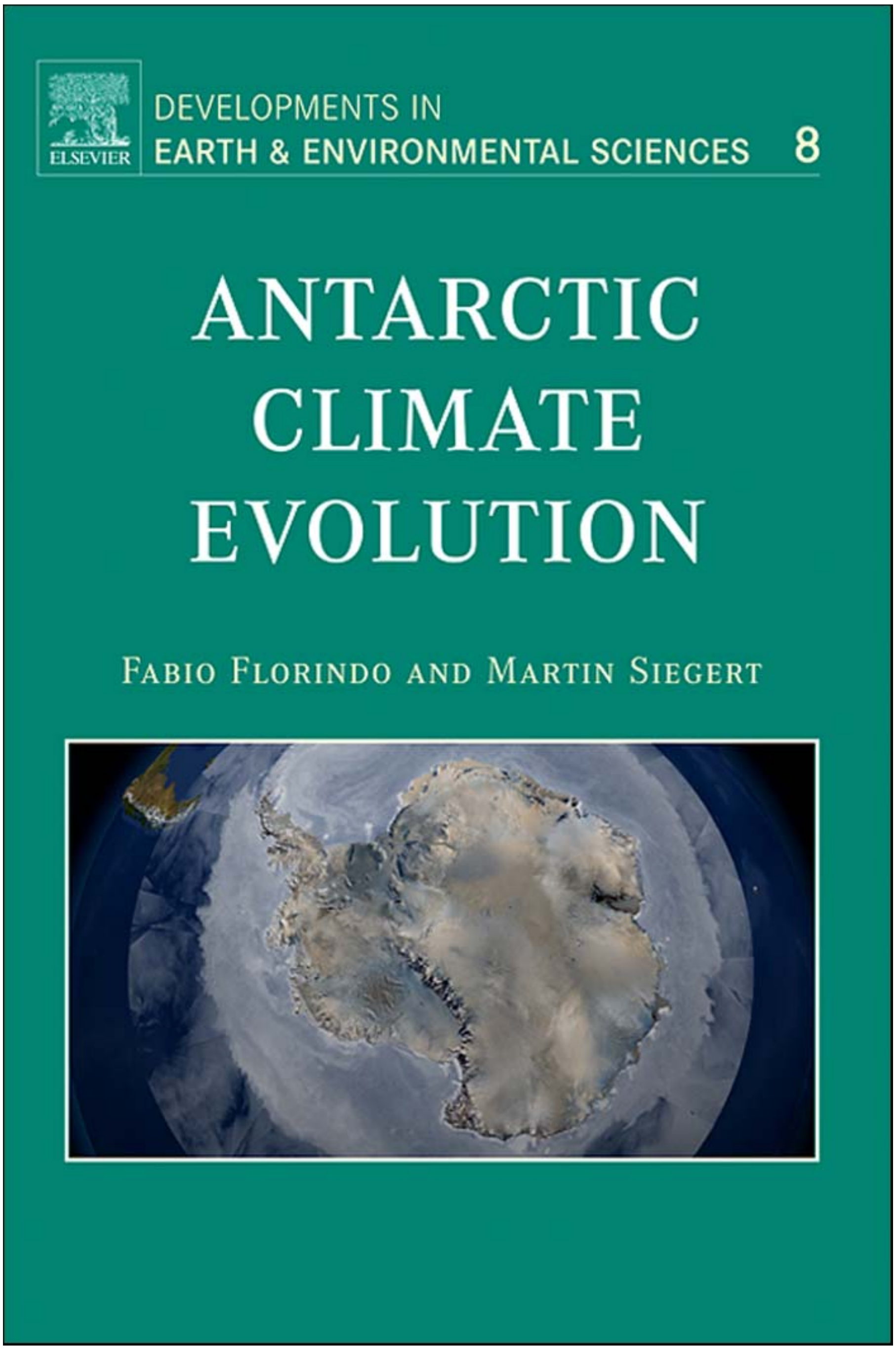

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Chapter 5

Cenozoic Climate History from Seismic Reflection and Drilling Studies on the Antarctic Continental Margin

Alan K. Cooper[1,*], Giuliano Brancolini[2], Carlota Escutia[3], Yngve Kristoffersen[4], Rob Larter[5], German Leitchenkov[6], Phillip O'Brien[7] and Wilfried Jokat[8]

[1]*Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94306, USA*
[2]*Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, B.go Grotta Gigante 42/c, 34010 Sgonico, Trieste, Italy*
[3]*Instituto Andaluz de Ciencias de la Tierra, CSIC-Univ. de Granada Campus de Fuentenueva s/n, 18002 Granada, Spain*
[4]*Department of Earth Science, University of Bergen, Allègaten 41, N-5007 Bergen, Norway*
[5]*British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK*
[6]*Research Institute for Geology and Mineral Resources of the World Ocean, VNIIOkeangeologia, 1 Angliysky Avenue, 190 121 St. Petersburg, Russia*
[7]*Geoscience Australia, Cnr Jerrabomberra Avenue and Hindmarsh Drive, GPO Box 378, Canberra ACT 2601, Australia*
[8]*Alfred-Wegener Institute, Am Handelshafen 12, D-27570 Bremerhaven, Germany*

ABSTRACT

Seismic stratigraphic studies and scientific drilling of the Antarctic continental margin have yielded clues to the evolution of Cenozoic climates, depositional paleoenvironments and paleoceanographic conditions. This paper draws on studies of the former Antarctic Offshore Stratigraphy Project and others to review the geomorphic and lithostratigraphic offshore features that give insights into the long-duration (m.y.) and short-term (k.y.) changes that document the great variability of Cenozoic Antarctic paleoenvironments. The lithologic drilling record documents non-glacial (pre-early Eocene) to full-glacial (late Pliocene to Holocene) times, and documents times of cyclic ice-sheet fluctuations at k.y.

*Corresponding author. Tel.: +01 650329 5157
E-mail: akcooper@pacbell.net (A.K. Cooper).

scales (early Miocene to Pliocene and Holocene). Times of significant change in types and/or amounts of glaciation are also seen in the offshore lithologic record (early Oligocene, mid-Miocene, early Pliocene). Seismic data illustrate large-scale geomorphic features that point to massive sediment erosion and dispersal by ice sheets and paleoceanographic processes (e.g. cross-shelf troughs, slope-fans, rise-drifts). The commonality of these features to East and West Antarctica since late Eocene time points to a continent that has been intermittently covered, partially to completely, by glaciers and ice sheets. The greatest advances in our understanding of paleoenvironments and the processes that control them have been achieved from scientific drilling, and future progress depends on a continuation of such drilling.

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5.1. Introduction

The Antarctic continental margin is a tectonic collage of former rifts and subduction zones that are covered by sediments deposited when the adjacent continent was free of regional glaciers (i.e. 'pre-ice-sheet' times) and when glaciers extended onto the margin (i.e. glacial times). Since the 1960s, many seismic surveys and sea-floor cores and a few drill cores have been acquired on the continental margin to decipher the Cenozoic and earlier history of Antarctica's paleoenvironments and paleoclimates – a history hidden onshore in sediments now unreachable beneath the Antarctic Ice Sheet. This chapter summarizes principally key results of seismic and drilling studies for proximal parts of the continental margin done from 1989 to 2004 by the multinational Antarctic Offshore Statigraphy project (ANTOSTRAT) to decipher Antarctic Ice Sheet history. We include some findings of the successor Antarctic Climate Evolution project (ACE) that includes the Cenozoic Antarctic Stratigraphy and Paleobathymetry project (CASP), to create a unified circum-Antarctic stratigraphy from all existing seismic and rock-core data (Davey and Cooper, 2007). Our summary complements istotopic and ice-rafting studies for distal parts of the margin and abyssal areas (e.g. Warnke et al., 1996; Zachos et al., 2001). We first describe work in five geographic sectors of the margin, and then summarize key results for the entire margin.

Multichannel seismic (MCS) reflection data, the principal tool for deep stratigraphic studies of the continental margin, have been recorded by more than 15 nations (Fig. I-1). Many topical MCS studies with maps of select regional data exist (see citations in regional sections below), but few comprehensive data compilations are either published or openly accessible. Notable exceptions are drilling results (e.g. Deep Sea Drilling Project, Ocean Drilling Program, Cape Roberts Project, ANDRILL and other drilling projects), MCS data compilations in the Antarctic Seismic Data Library System (e.g. www.scar-sdls.org; Wardell et al., 2007), a few Antarctic and regional geosciences atlases (e.g. Hayes, 1991; Cooper et al., 1995), online

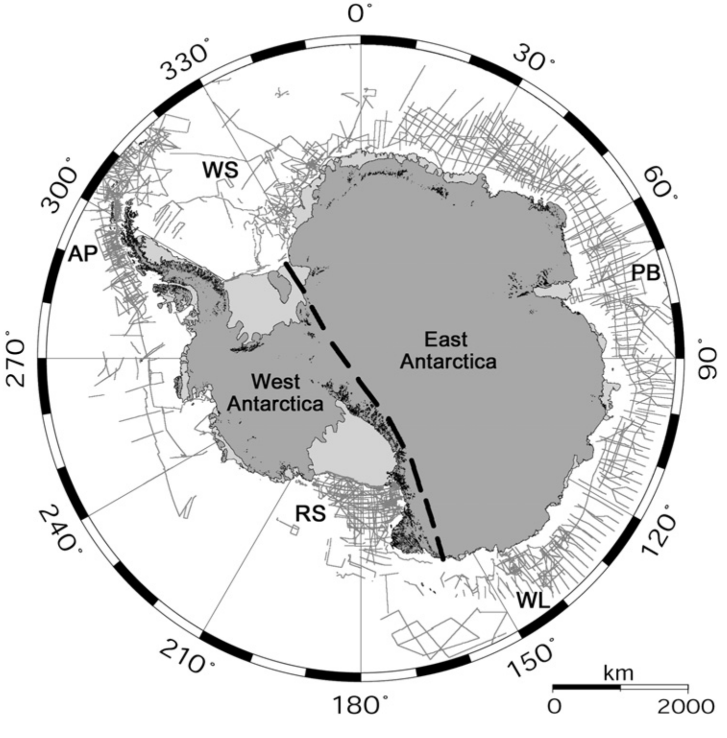

Figure I-1: Map showing locations of tracklines for multichannel seismic-reflection data on the Antarctic continental margin as of late 2006 (from Wardell et al., 2007). Regions are RS, Ross Sea; WL, Wilkes Land; PB, Prydz Bay; WS, Weddell Sea; AP, Antarctic Peninsula.

data centres (e.g. World Data Center) and select discussions of Antarctic margin databases (e.g. Anderson, 1999).

In general, Antarctica had a relatively warm climate and normal-water-depth continental shelf (i.e. like low-latitude continental shelves today) in earliest Cenozoic and Late Cretaceous times – conditions that differ from the polar climate of the latest Cenozoic, with its thick ice sheet and an abnormally deep-water-depth and landward sloping shelf (e.g. Cooper et al., 1991b; Anderson, 1999). Ice has played an important role in continental margin evolution by eroding onshore areas (formerly with vegetation) and discharging the debris into the sea, where ocean currents distribute it to the continental shelf, slope and rise. At times the ice has strongly eroded parts of the shelf. Tectonic processes, principally variable thermal and flexural subsidence and uplift, have also modified the margin morphology and hence stratigraphy (e.g. ten Brink et al., 1995).

Offshore Antarctic stratigraphic studies have thus focused on mapping geomorphology and seismic facies of characteristic features (e.g. shelf-edge fans/deltas, mound deposits, unconformities, etc.), and using the limited core and downhole data to decipher their depositional paleoenvironments and relation to nearby ice, if any. Such features help to infer and establish where and when non-glacial and glacial processes acted (e.g. Cooper et al., 1991b). Drilling is the only way to 'ground truth' the regional seismic surveys (i.e. via a direct tie of lithologic facies to seismic facies), and to provide the age and biostratigraphic control needed to decipher depositional and climatic paleoenvironments (e.g. Barker and Camerlenghi, 2002; Cooper and O'Brien, 2004). The following regional subchapters have been written by the regional experts listed. Their bibliographic citations are augmented in a 'selected reference' section that provides additional background on the prior studies done by the Antarctic geoscience community.

5.2. Ross Sea (G. Brancolini and G. Leitchenkov)

The Ross Sea has four large sedimentary basins with thick Cenozoic sequences that record the proximal paleoenvironmental histories of the East and West Antarctic Ice Sheets (Cooper and Davey, 1985; Cooper et al., 1991b, c). Here, ice-sheet evolution is linked to the Cenozoic uplift histories of the Transantarctic Mountains and Marie Byrd Land. Offshore, the West Antarctic Ice Sheet (WAIS) flows across the Eastern basin, and the East Antarctic Ice Sheet (EAIS) passes over the Transantarctic Mountains and flows across the Victoria Land basin, the Northern basin and the Central trough (Fig. RS-1).

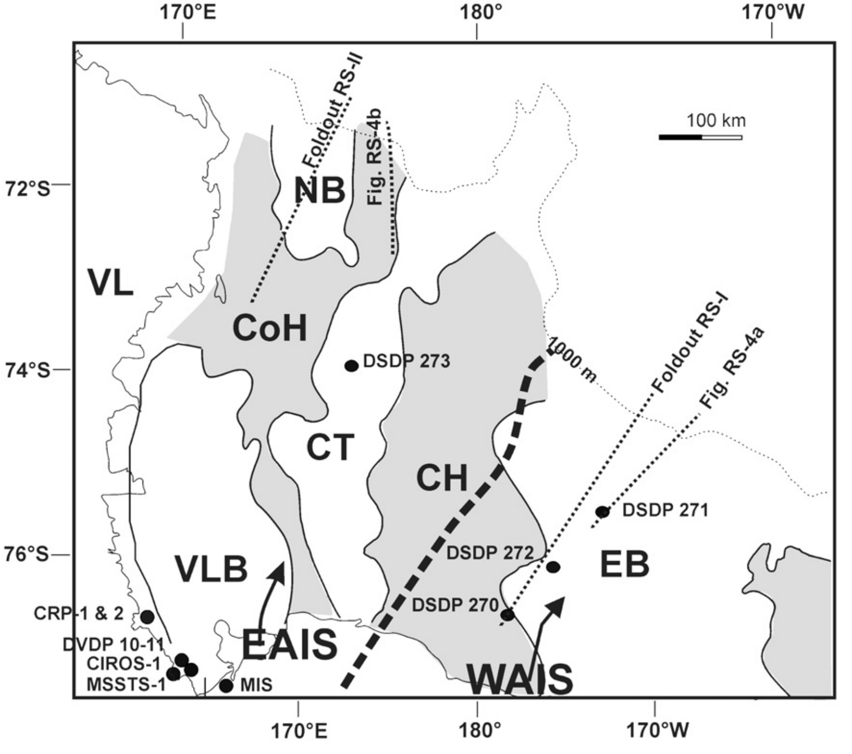

Figure RS-1: Map showing the structural framework of the ross sea. The limits of the basins are based on the depositional limits of the seismic Sequence RSS-1. VL, Victoria Land; VLB, Victoria Land basin; NB, Northern basin; CoH, Coulman high; CH, Central high; CT, Central trough; EB, Eastern basin; WAIS, West Antarctic Ice Sheet; EAIS, East Antarctic Ice Sheet. The heavy dashed line marks the postulated boundary between East Antarctic Ice Sheet and West Antarctic Ice Sheet drainage.

Numerous seismic studies have been done in the Ross Sea region since the 1960s, with more than 45,000 km of MCS reflection data collected since 1980 (Hinz and Block, 1984; Sato et al., 1984; Cooper and Davey, 1987; Hinz and Kristoffersen, 1987; Zayatz et al., 1990; Brancolini et al., 1991) (Fig. RS-2a), to provide tectonic and deep stratigraphic control. A large number of single-channel seismic (SCS) surveys have also been conducted for greater resolution of the shallow subsurface (Fig. RS-2b). Drilling at several sites by DSDP (Deep Sea Drilling Project, Hayes and Frakes, 1975), DVDP (Dry Valley Drilling Project, McGinnis, 1981), MSSTS (McMurdo Sound Sediment and Tectonic Study, Barrett, 1986), CIROS (Cenozoic Investigation in the Western Ross Sea, Barrett, 1989) and CRP (Cape Roberts Project,

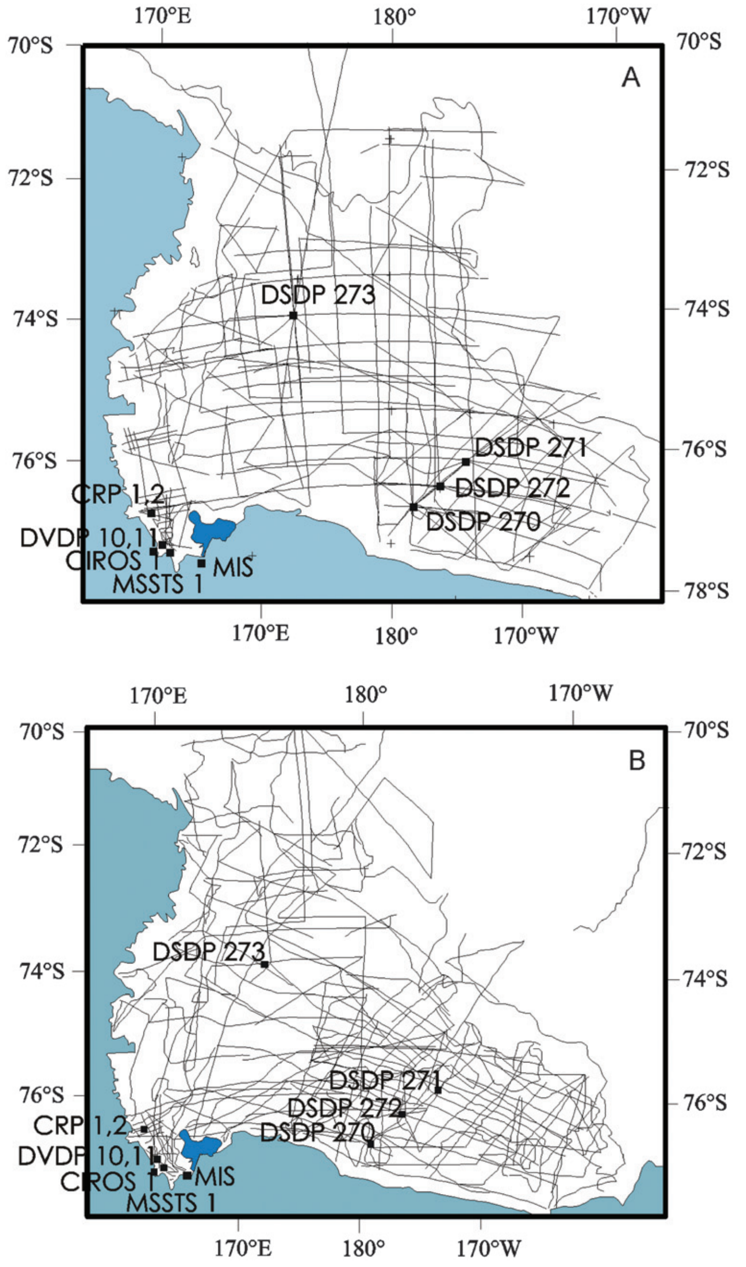

Figure RS-2: (A): Multichannel seismic-reflection surveys in the Ross Sea (modified from Brancolini et al., 1995). Some of these data are available in digital format from Cooper et al. (1995) and others from the Antarctic Seismic Data Library (Childs et al., 1994; Wardell et al., 2007). (B) Single-channel seismic surveys in the Ross Sea (modified from Barrett et al., 1999).

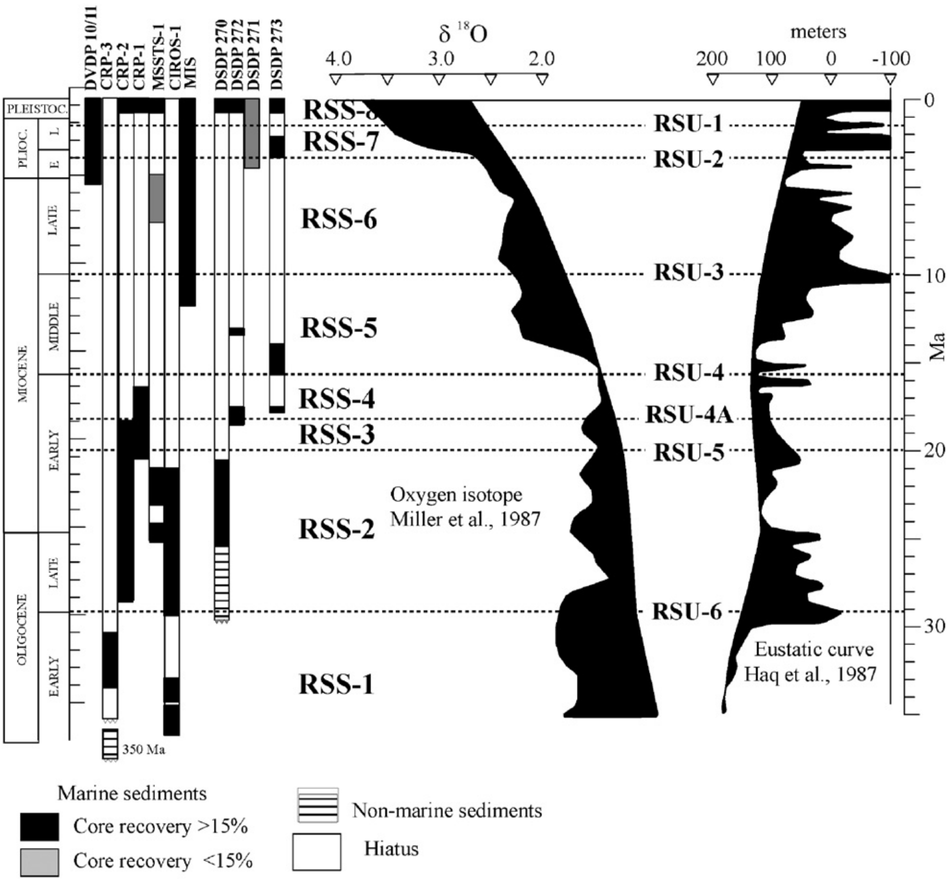

Figure RS-3: Correlation of Ross Sea area drilling and seismic stratigraphy with global oxygen isotope (Miller et al., 1987) and eustacy (Haq et al., 1987) curves (modified from Brancolini et al., 1995; Cooper et al., 1995). Regional erosional unconformities in Oligocene and younger sections are interpreted to be due in part to sub-ice erosion, especially in late Neogene time.

Cape Roberts Science Team, 1998, 1999, 2000, 2001) ANDRILL (Antarctic geological Drilling, Naish et al., 2007; Florindo et al., 2008; Harwood et al., 2008) provides geologic ground truth data (Fig. RS-3). A regional seismic stratigraphy has been derived by the ANTOSTRAT project with seismic sequences and unconformities tied to drilling data (Fig. RS-3; Cooper et al., 1995).

Ross Sea seismic data are used by many to infer glacial sedimentary processes (e.g. Cooper et al., 1991b; Alonso et al., 1992; Anderson and

Bartek, 1992; Shipp et al., 1994; Brancolini et al., 1995; Cochrane et al., 1995; De Santis et al., 1995; Bartek et al., 1996; De Santis et al., 1999; Bart et al., 2000; Bart, 2003; Chow and Bart, 2003; Accaino et al., 2005). Characteristic features and inferred processes in Oligocene and younger strata include:

1. Landward-deepening seafloor of the continental shelf with broad (up to 100 km wide) cross-shelf troughs and banks formed by ice-stream erosion and deposition, respectively.
2. Numerous regional seismic unconformities believed to result from erosion of the continental shelf by grounded ice sheets.
3. Steep prograding sedimentary sequences (i.e. foreseest dips more than 5° and eroded topset strata) interpreted as ice-proximal till deltas from grounded ice.
4. Wedge-shape, non-reflective units interpreted as 'till tongues' deposited by grounded ice.
5. Shallow sediment with high velocities, considered due to overcompaction by grounded ice.

The seismic stratigraphy and drilling help establish ice-sheet evolution in the Ross Sea region, and are discussed below for four key intervals.

5.2.1. Pre-Ice-Sheet (Pre-Late-Oligocene Time)

This period includes seismic sequence RSS-1 between the acoustic basement and unconformity RSU-6 (Fig. RS-3, Foldouts RS-1 and RS-2) and, in the Victoria Land basin, acoustic units V4 and V5 (Cooper et al., 1987).

Acoustic basement rocks have been sampled at two sites, and are Palaeozoic Beacon Formation rocks at the CRP-3 site adjacent to the coast (Cape Roberts Science Team, 2000) and are inferred palaeozoic and Cretaceous igneous and metamorphic rocks at DSDP Site 270 in the centre of the Ross Sea (Hayes and Frakes, 1975). The basins are believed to hold sedimentary rocks of Cretaceous and younger age (Hinz and Block, 1984; Cooper et al., 1991c), but Sedimentary rocks older than late Eocene have not been cored by drilling. Upper Eocene sediments have been cored in the CIROS-1 drillhole in McMurdo Sound (Coccioni and Galeotti, 1997; Fielding et al., 1997; Hannah et al., 1997; Monechi and Reale, 1997). The presence of ubiquitous lonestones (Barrett, 1989) testifies that glaciers (but not necessarily continent-size ice sheets) were calving at sea-level then.

Eocene erratic rocks are found in coastal areas (Levy et al., 1995), and have flora indicating cool, but not glacial, climates in the McMurdo area (Stillwell and Feldmann, 2000). Offshore basin analysis, mainly from MCS reflection data, suggests that in Cenozoic pre-ice-sheet times, the Ross Sea was dissected by high-standing subaerial ridges, now seen as the buried Coulman high and Central high (De Santis et al., 1995). Prior outcropping of these ridges is suggested by the presence of regoliths above the basement at DSDP Site 270 (Hayes and Frakes, 1975).

5.2.2. Early Glacial (Late Oligocene to Early Miocene)

This period includes seismic sequences RSS-2 and -3 (Fig. RS-3 and Foldouts RS-1 and RS-2). Sedimentary rocks from this period were recovered at CIROS-1, and CRP-1, -2 and -3, and MSSTS-1 drilling sites in the McMurdo Sound area. Such rocks include compacted diamicton indicative of deposition by/under grounded ice, as well as mud and ice-rafted debris (IRD) indicative of open-water environments (Barrett, 1986; Barrett, 1989; Hannah, 1994; Cape Roberts Science Team, 2001), in lower Miocene sediments at CRP 2/2A sites. Compacted diamicton and mud layers at site CRP-1, vary with uniform cyclicity, and document systematic oscillation of the EAIS size (Naish et al., 2001). The oscillations are at orbital periodicities similar to those recorded by isotope studies in distal deep-ocean sediments.

Seismic facies along the border of the Victoria Land basin suggest that tidewater glaciers all along the Transantarctic Mountains intermittently extended onto the continental shelf and carried abundant glacial sediment to the sea (Brancolini et al., 1995; Bartek et al., 1996; Henrys et al., 2001).

In the eastern Ross Sea, at DSDP Site 270, *Nothofagus*-dominated flora in lower Miocene sediments (Kemp and Barrett, 1975) are similar to those recovered in McMurdo Sound drillcores (Hill, 1989; Mildenhall, 1989; Askin and Raine, 2000), and indicate cool-temperate climates during interglacial periods. DSDP Site 270 also recovered lower Miocene ice-proximal glaciomarine sediments from the early Miocene section, but the size and character of the ice sheet that deposited these sediments is debated. Anderson and Bartek (1992) suggest, based on high-resolution single-channel seismic data and drill cores, that by late Oligocene to early Miocene time, the continental shelf was deeply scoured and foredeepened (i.e. landward dipping) by a massive ice sheet. In contrast, Brancolini et al. (1995) and De Santis et al. (1995), utilize regional stratigraphic maps (Cooper et al., 1995) and their seismic facies analyses to postulate that, during the same period the Central high was partly exposed and partly covered by small subpolar ice caps (i.e. subpolar as defined by Anderson and Ashley, 1991). A semi-quantitative evaluation of the water depth of the Eastern basin during the early Miocene, based on the backstripping of the seismic section in Foldout RS-1, indicates that the foredeepeened profile of the Eastern basin was only attained after middle Miocene time (De Santis et al., 1999).

The end of this early glacial period is marked by a change in reflection geometries beneath the outer continental shelf (Foldouts RS-1 and RS-2) from principally aggrading (RSS-2 and -3) to principally prograding, (RSS-4). Cooper et al. (1991b) postulate that this change marks the start of grounded-glacier advances to the shelf edge and erosion of a normal-water-depth shelf by episodic grounded ice.

5.2.3. The Ice-Sheet Development (Mid-Early Miocene to Early Pliocene)

This period includes seismic sequences RSS-4, -5 and -6 (Fig. RS-3 and Foldouts RS-1 and RS-2). Sediment from these sequences was recovered at DSDP Sites 271, 272 and 273, MSSTS-1 and DVDP 10/11.

The early-middle Miocene is postulated to have been a time of major ice buildup of ice in the Ross Sea region, and the carving of the first deep troughs, similar in size to the present ice streams, across the continental shelf (Anderson and Bartek, 1992). Bart (2003) and Chow and Bart (2003) recognize at least two major WAIS expansions during the early part of the middle Miocene and five in the entire Miocene. These expansions suggest that either portions of the West Antarctic land elevation were above sea-level and/or the air and water temperatures were sufficiently cold to support a marine-based ice sheet.

Drill cores from the middle Miocene have been recovered at DSDP Sites 272 and 273 (Hayes and Frakes, 1975; Savage and Ciesielsky, 1983; Leckie and Webb, 1986), and consist of diatom-bearing sediments interpreted as waterlain tills and proximal- to distal-glacimarine deposits (Hambrey and Barrett, 1993).

Upper Miocene rocks are missing from all continental shelf drill cores, except in the McMurdo Sound region (MSSTS-1, DVDP-10 and -11 drill sites), where glaciomarine diamictites (tillites) and terrestrial strata are found. These deposits are interpreted as having originated from glaciers flowing out of the Transantarctic Mountains (Powell, 1981; Barrett, 1986; Ishman and Webb, 1988; McKelvey, 1991).

The recent ANDRILL drilling on the Ross Ice shelf, near McMurdo Sound (MIS project; Naish et al., 2007), recovered a 1,284 m long core that records Antarctica's history over the last 14 million years. The core indicates periods of ice-sheet growth, advancing over the drill site and then retreating again to allow the open-marine conditions to return. More than 60 of these advance-retreat cycles are present in the core.

On the outer continental shelf and upper slope, well-stratified seismic sequences inferred to be of late Miocene age (i.e. RSS-6) are present in the

Northern and Eastern basins, but the sequences are thin or absent on the inner shelf (Cooper et al., 1995). In both basins, these sequences are characterized by steeply prograding clinoforms with relatively thin or eroded topset beds and a major seaward shift of the palaeo-shelf edge (Foldouts RS-1 and RS-2). The sequences are thought to have been deposited by intermittent grounded ice sheets carrying sediment to the continental shelf edge (Bartek et al., 1991; Cooper et al., 1991b; Anderson and Bartek, 1992).

5.2.4. The Polar Ice Sheet (Early Pliocene Through Quaternary)

This period includes seismic sequences RSS-7 and -8 (Fig. RS-3) and seismic units 1–7 of Alonso et al. (1992) and Anderson and Bartek (1992) (Fig. RS-4a and b). Pliocene sediment has been recovered at drill sites in the Taylor Valley (DVDP-10 and -11) and on the continental shelf at DSDP Sites 271 and 273. DVDP drill cores contain sediments deposited by the Taylor Glacier, while the sparsely sampled Pliocene deposit at DSDP 271 and 273 contains diatomaceous glaciomarine strata (Hayes and Frakes, 1975). These rocks imply that warmer interglacial conditions than today existed at that time (Anderson and Ashley, 1991).

Seismic sequences of inferred Pliocene through Quaternary age occur in the EAIS drainage in the Northern basin, where they are up to 800 m thick in the till delta fan system (Cooper et al., 1995). In the Eastern basin, Pliocene through Quaternary age strata lie within the WAIS drainage and are more than 1,000 m thick (Cooper et al., 1995). Detailed seismic stratigraphic analyses from the Eastern basin margin (Fig. RS-4a; Alonso et al., 1992; Fig. RS-4b; Anderson and Bartek, 1992), recognize a major change in the seismic character of the Pliocene deposits. Up-section, the seismic unit thicknesses decrease, the geometry of the sequences changes from principally progradational to aggradational, and numerous widespread glacial erosion surfaces are seen. These features indicate more frequent grounding events on the continental shelf and increased subglacial till deposition relative to basal transport of sediments to the grounding line. Bart et al. (2000) and Anderson et al. (1992) suggest that on at least eight occasions during Pliocene to Quaternary times, the East and West Antarctic Ice Sheets were much larger than today. The frequent and extensive grounding events on the outer continental shelf contradict the widely held view that the land-based EAIS was relatively stable and the largely marine-based WAIS was relatively dynamic (Bart and Anderson, 2000).

The last glacial maximum (LGM) in the Ross Sea has been studied using seafloor cores, subbottom and swath bathymetry data (Thomas and Bentley, 1978; Kellogg et al., 1979; Denton et al., 1989; Leventer et al., 1993; Brambati et al., 1994; Hilfinger et al., 1995; Kellogg et al., 1996; Licht et al.,

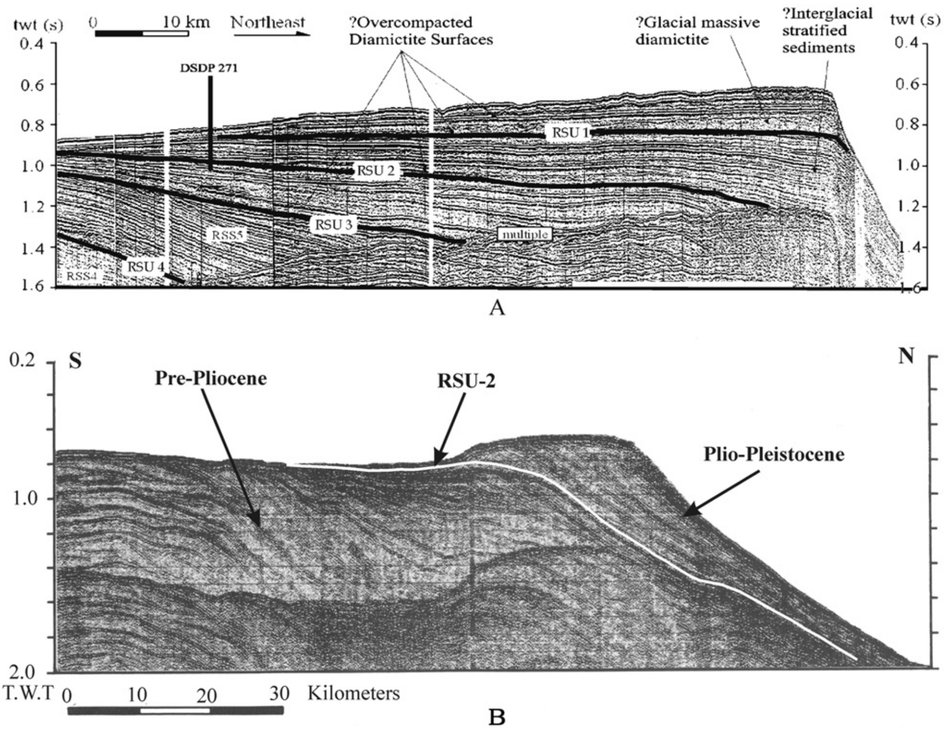

Figure RS-4: Seismic-reflection profiles across the Eastern basin (A) and the Northern basin (B), illustrating the Neogene stratigraphic sections (from Anderson and Bartek, 1992). The shelf margin delta fan complex shown is a common feature in the seismic data from the continental margin and characterizes deposition close to the ice-sheet grounding line. See Fig. RS-1 for location.

1996; Cunningham et al., 1999; Domack et al., 1999; Licht et al., 1999; Shipp et al., 1999; Alley and Bindschadler, 2001). Radiocarbon dates from diamictons and sediment composition, indicate that ice-free conditions existed on the inner shelf at times during the period from 60 to 10 ka, and that the ice sheet was present between 26.5 and 19.5 ka. (Domack et al., 1999). The maximum ice-sheet expansion in the LGM is still debated: Kellogg et al. (1996) place the grounding line at the continental shelf edge, Domack et al. (1999) put it just north of the Coulman Island and Licht et al. (1999) interpret that it was about 100 km south of Coulman Island. The last retreat of the grounding line occurred in the western Ross Sea around 11 ka at a rate of about 100 m/year, and the grounding line reached its present position about 6 ka (Domack et al., 1999; Shipp et al., 1999).

5.3. Wilkes Land (C. Escutia and P. O'Brien)

5.3.1. Acoustic Stratigraphy

The approximately 1,500 km long Wilkes Land segment of the continental margin (Fig. WL-1) formed during the Cretaceous separation of Australia and Antarctica (Cande and Mutter, 1982; Veevers, 1987; Sayers et al., 2001; Colwell et al., 2006; Leitchenkov et al., 2007; O'Brien and Stagg, 2007).

The stratigraphy of the margin is known mainly from the seismic stratigraphic interpretation of numerous MCS surveys (Sato et al., 1984; Wanneson et al., 1985; Tsumuraya et al., 1985; Eittreim and Hampton, 1987; Ishihara et al., 1996; Tanahashi et al., 1997; Brancolini and Harris, 2000; Stagg et al., 2004a, b); complemented by surface sediment cores (Domack et al., 1980; Payne and Conolly, 1972; Domack, 1982; Tsumuraya et al., 1985; Hampton et al., 1987; Ishihara et al., 1996; Tanahashi et al., 1997; Brancolini and Harris, 2000; Leventer et al., 2001; Escutia et al., 2003; Michel et al., 2006); and limited deep geological sampling recovery at DSDP Sites 268 and 269 (Hayes and Frakes, 1975). The best-surveyed area is the eastern Wilkes Land margin (EWL) from the Adélie Coast to George V Land. West of this area (the western Wilkes Land margin-WWL), Japan and Russia collected widely spaced seismic lines that were then augmented during the 2001–2002 Australian Antarctic and Southern Ocean Profiling (ASSOPP) Project (Stagg et al., 2004a, b; Leitchenkov et al., 2007).

5.3.1.1. Pre-ice-sheet stratigraphy

Along the Wilkes Land margin syn- and post-rift sedimentary rocks reach thicknesses of more than 7 km (Stagg et al., 2004a, b). Pre-Eocene syn-rift strata are about 3 km thick and are highly variable in seismic character, with discontinuous, faulted, and tilted strata onlapping the flanks of the acoustic basement (Eittreim and Smith, 1987; Eittreim, 1994; De Santis et al., 2003; Stagg et al., 2004a, b; Leitchenkov et al., 2007).

The thickest (at least 9 km) depocentre of post-rift sedimentary rocks is located in the WWL off the Bud Coast (Close et al., 2007). In the EWL post-rift strata are up to 5 km thick across the Wilkes Land continental shelf, slope and rise (Eittreim and Smith, 1987; Hampton et al., 1987; Wannesson, 1990; Tanahashi et al., 1994; De Santis et al., 2003). These strata are well-layered on the continental rise and become less stratified and more discontinuous landward (Eittreim and Smith, 1987; Eittreim, 1994;

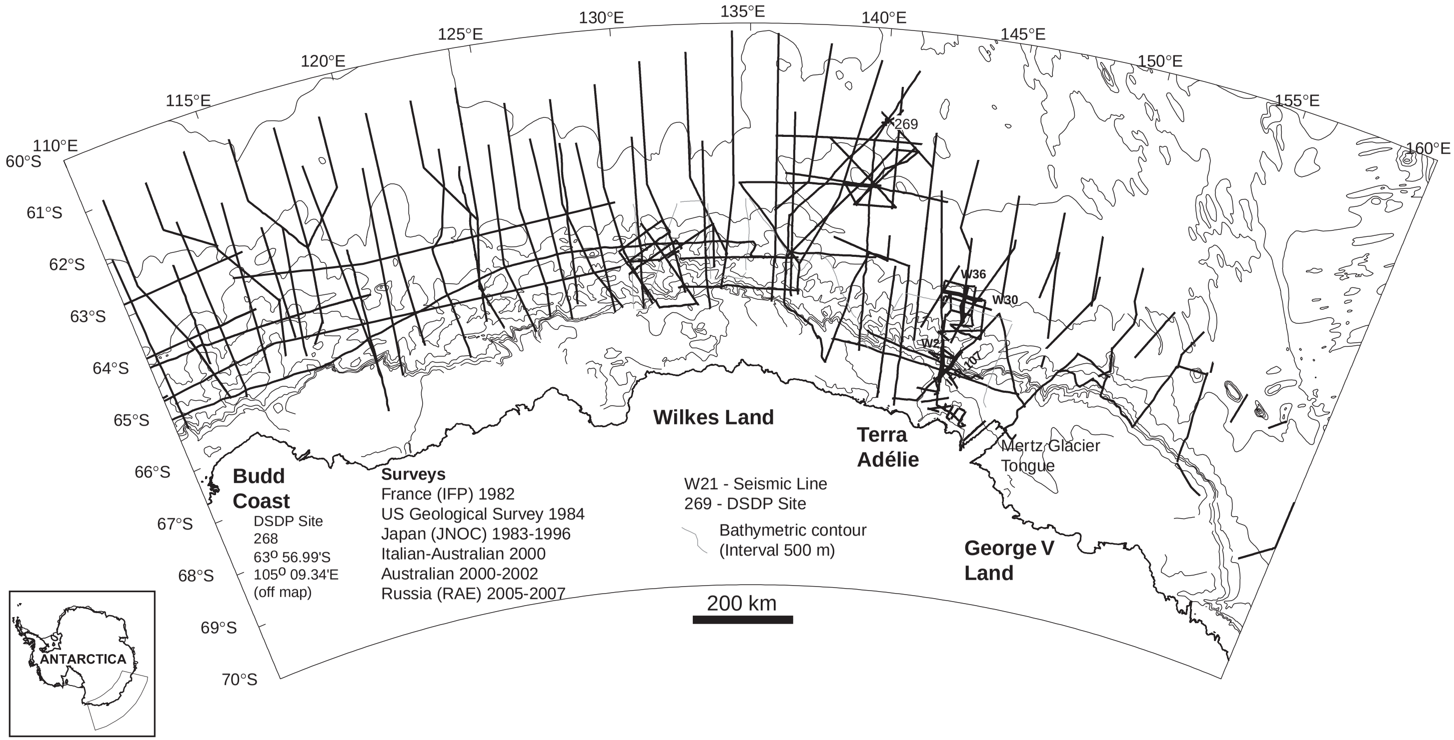

Figure WL-1: Location of multichannel seismic-reflection profiles collected on the Wilkes Land margin. Location of the seismic sections shown in Figs. 2 and 3 is indicated.

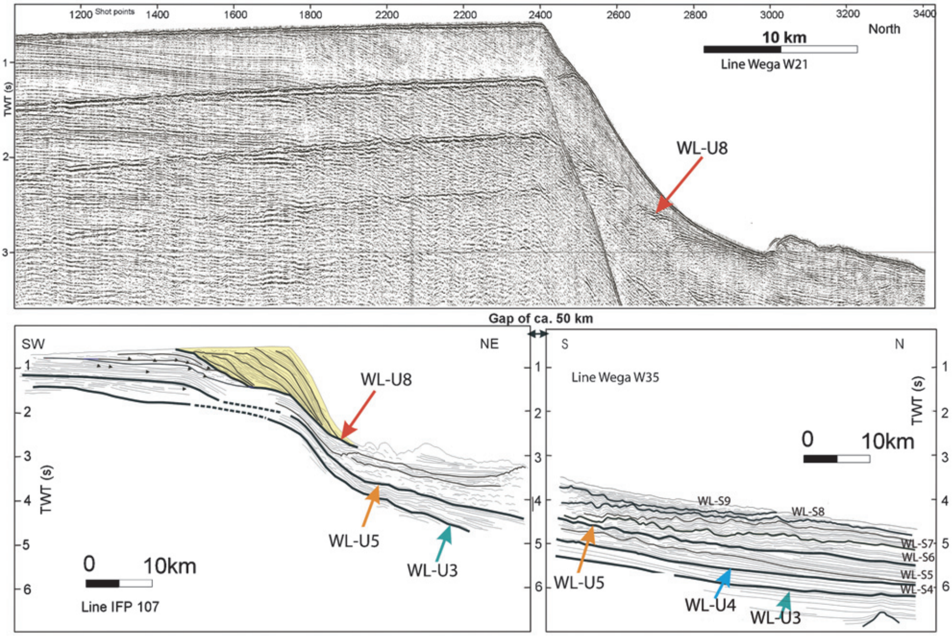

Figure WL-2: Multichannel seismic line WEGA W21 and line drawings of multichannel seismic profiles IFP 107 and WEGA W35 showing the overall architecture of the Wilkes Land margin from the continental shelf to the continental rise (modified from Escutia et al., 2005). See Fig. WL-1 for location of the seismic lines.

De Santis et al., 2003). A prominent regional unconformity (WL-U3) within the Cenozoic post-rift section beneath the continental shelf (Fig. WL-2) is believed to be due to erosional processes related to the first advance of grounded ice sheets onto the continental shelf (Eittreim and Smith, 1987; Tanahashi et al., 1994; Eittreim et al., 1995; Escutia et al., 1997; Escutia et al., 2005). The pre-ice-sheet strata below unconformity WL-U3, where resolvable, are flat-lying and less stratified than glacial strata above the unconformity.

Pre-ice-sheet rocks have been dredged from the Wilkes Land continental shelf and slope. On the inner shelf, Mesozoic sediments have been exposed via erosion by late Cenozoic glaciers near the Mertz ice tongue. Lignite was recovered (Mawson, 1940, 1942), and lower Cretaceous brecciated, carbonaceous siltstone was cored (Domack et al., 1980). Other dredge samples in the area, acquired by Leventer et al. (2001), include sedimentary clasts of Paleogene lignites with reworked Early Cretaceous flora. On the upper continental slope off Terre Adélie, Sato et al. (1984) dredged samples of locally derived Oligocene and Miocene limestone and undated sedimentary, metamorphic and igneous rocks of mostly ice-rafted origin.

5.3.1.2. Continental shelf glacial stratigraphy

Glacial sequences on the shelf thicken seaward in prograding wedges (Fig. WL-2). The sequences are deeply eroded by broad troughs that cross the shelf. The troughs are interpreted as the erosional paths of ice streams during times of glacial maxima (Eittreim et al., 1995). Foreset strata are commonly truncated at or near the seafloor beneath the troughs (Fig. WL-2). Topset strata form the banks adjacent to the troughs. Ice is inferred to have moved slowly over bank areas and rapidly in the troughs. Geometry of strata in buried troughs on the shelf suggests to some (Eittreim et al., 1995; Escutia et al., 2000) that the locations of ice streams and their erosional troughs and banks have shifted during consecutive glacial advances.

Regional glacial seismic sequences and unconformities defined by different workers (Table WL-1) in the EWL were renamed and in some cases redefined by De Santis et al. (2003). On the shelf, sequences are truncated by two

Table WL-1: Summary of the terminology assigned in previous publications to the inferred wilkes Land glacial sequences and their bounding unconformities (updated from Escutia et al., 2005). Unconformities (tied with lines) and sequences (in between these lines) are listed from younger at the top to older.

Wanneson (1991)	Eittreim and Smith (1987)	Tanahashi et al. (1994), Eittreim et al. (1995)	Escutia et al. (1997, 2000)	De Santis et al., 2003	Close et al. (2007)	Leitchenkov et al. (2007)
			Phase 3 ——	WL-S9		
		WL1 ——	WL1 ——	WL-U8		
			Phase 3	WL-S8		
				WL-U7		
			Phase 2	WL-S7		
				WL-U6		
		A2	Phase 1	WL-S6		
			WL1b ——	WL-U5 ——	——	WL5
	A2			WL-S5		
	UNCONF ——	——	WL1c ——	WL-U4 ——	——	WL4
Unit 3	A1	B		WL-S4		
	T ——	WL2 ——	WL2 ——	WL-U3 ——	eoc ——	WL3

regional unconformities, WL-U3 and WL-U8 (Wannesson et al., 1985; Eittreim and Smith, 1987; Hampton et al., 1987; De Santis et al., 2003), and the erosion is thought to result from grounded ice sheets moving across the continental shelf (Tanahashi et al., 1994; Eittreim et al., 1995; Escutia et al., 1997; Escutia et al., 2005). Eittreim et al. (1995) calculated erosion of 300 to 600 m of strata below WL-U3. Sequences below WL-U8 are dominantly aggradational and sequences above are principally progradational. For unconformity WL-U8, Eittreim et al. (1995) estimated erosional truncation of 350 to 700 m of sediment. Unconformity WL-U8 marks changes in the geometry of the outer shelf progradating wedges, from shallower dips below WL-U8 to steeper dips above (foreset slopes up to about 10°).

During the open-marine Holocene, thick laminated diatom mud and oozes were deposited in deep (>1,000 m) inner shelf basins, such as for example the Adélie Drift (Costa et al., 2007). Based on AMS radiocarbon dates, this drift has accumulation rates on the order of 20–21 m/k.y. Opal, Ti and Ba time-series show decadal to century variance suggestive of solar forcing and El Niño Southern Oscillation (ENSO) forcing (Costa et al., 2007).

5.3.1.3. Continental slope glacial stratigraphy

Although partly obscured by seafloor multiples, the stratigraphy of the continental slope consists of seaward-dipping reflectors (Eittreim and Smith, 1987; Hampton et al., 1987; Eittreim et al., 1995). Prograding strata above the WL-U8 unconformity downlap and pinch out at the base of the continental slope, but deeper units (i.e. between WL-U8 and WL-U3) continue across the margin (Hampton et al., 1987; Eittreim et al., 1995; Escutia et al., 1997; De Santis et al., 2003) (Fig. WL-2).

Sediments forming prograding foresets were delivered directly to the outer shelf and upper slope as deforming tills at the base of ice streams at times of glacial maxima (Eittreim et al., 1995). Ice-stream delivery of a large volume of unconsolidated sediment to the steep slope resulted in sediment failures that led to the development of large chaotic deposits at the base of the paleoslope foresets (Eittreim et al., 1995; Escutia et al., 2000; De Santis et al., 2003; Escutia et al., 2007). More-recent slope strata are dissected by erosional submarine gullies (Eittreim et al., 1995) and slope canyons (Escutia et al., 2000).

Sea-floor sediment cores from the continental slope contain debris-flow units and numerous hiatuses. The oldest sediment has been dated as late Miocene in age, indicating that gravity flows have been a dominant slope process since at least this time (Escutia et al., 2003).

5.3.1.4. Continental rise glacial stratigraphy

On the EWL continental rise, strata above the WL-U3 unconformity include six glacial-related seismic units, WL-S4 to WL-S9 (De Santis et al., 2003; Donda et al., 2003) (Table WL-1, Fig. WL-3). The two deepest units, WL-S4 and WL-S5, consist of stratified and continuous reflectors that onlap at the base of the slope (Escutia et al., 1997; Donda et al., 2003). Acoustic signatures of isolated channel-levee complexes that characterize turbidite deposition are first observed up-section within unit WL-S5 (Escutia et al., 1997; Escutia et al., 2000; Escutia et al., 2002; Donda et al., 2003). During deposition of units WL-S6 and WL-S7, channel-levee complexes became widespread and turbidity flows were the dominant process building the sedimentary ridges on the rise. Wavy reflectors that are characteristic of bottom contour-current deposition occur on the lower rise in unit WL-S6 and on the upper rise in WL-S7. Within Unit WL-S8, there is evidence for bottom contour-current and turbidite flows, but WL-S8 mostly infills previous depressions (Escutia et al., 1997; Escutia et al., 2000; Escutia et al., 2002; Donda et al., 2003). Unit WL-S9 is a discontinuous unit on the rise, and, where present, comprises channel and levee complexes and layered reflectors (Donda et al., 2003). Recent studies on the WWL margin glacial strata show a similar evolution of the glacial sedimentary sequences (i.e. increased proximal turbidite facies up-section and influence of bottom-contour-current deposition) above unconformities 'eoc' (Close et al., 2007) and WL3 (Leitchenkov et al., 2007), which correlate with WL-U3 on the

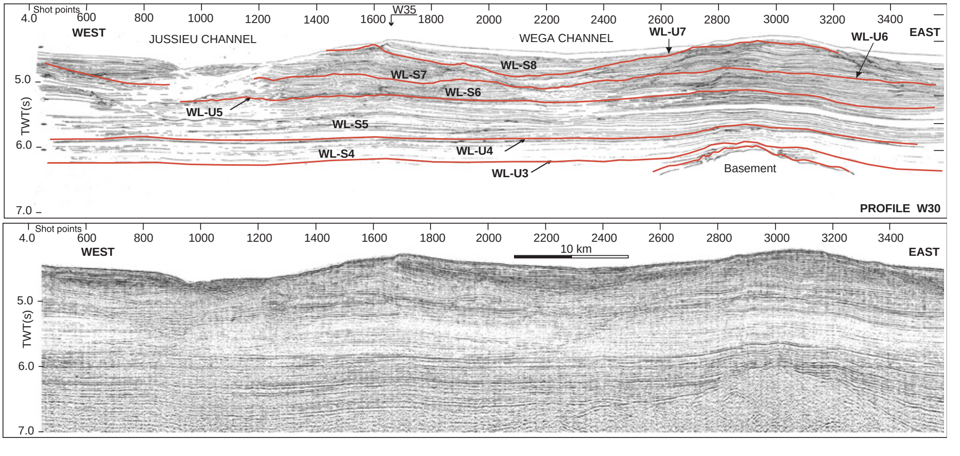

Figure WL-3: High-resolution multichannel line WEGA W30 across the distal continental rise. Also shown is a line drawing interpretation of this profile after Donda et al. (2003). Location of seismic line is shown in Fig. WL-1.

EWL. Between 110° and 130° large debris-flow deposits are also reported forming throughout the Miocene (Donda et al., 2007a, b).

5.3.2. Drilling on the Wilkes Land Margin

DSDP Leg 28 drilled Sites 268 and 269 on the continental rise and abyssal plain, respectively, to determine the geologic and climate history of Antarctica and the Southern Ocean (Hayes and Frakes, 1975). The drill cores document that extensive Antarctic glaciation began at least by Oligocene to early Miocene time, and that water temperatures were cool-temperate in the late Oligocene and early Miocene and cooled during the Neogene, presumably as glaciation intensified.

DSDP Site 268 was drilled to a subbottom depth of 474.5 m in 3,544 m water depth with total core recovery of 14% (Hayes and Frakes, 1975). Three units were described, based on lithologies and amounts of diatoms, nannofossil ooze and ice-rafted pebbles and granules (Hayes and Frakes, 1975). Piper and Brisco (1975) interpreted the two deeper units to be contourites, based on the character of silt laminae. The shallowest of the three units, dated as Pliocene and Quaternary, was interpreted as turbidites, based on a high content of silty clay with common silt laminae and fine-sand beds 2–20 cm thick. Hayes and Frakes (1975) infer that the deepest lower Miocene and Oligocene unit was deposited when the ice sheet first advanced onto the shelf. Water at that time was warm enough to support calcareous biogenic sedimentation, but ice-rafting and contourites provide evidence for nearby ice on East Antarctica and for bottom currents, possibly generated by cold bottom water production associated with a limited ice shelf or tongue (Hayes and Frakes, 1975).

DSDP Site 269 was drilled to a subbottom depth of 958 m in a water depth of 4,285 m and with 42% recovery of Eocene to recent rocks (Hayes and Frakes, 1975). The section consists predominantly of silts and clays with variable amounts of microfossils. Diatom oozes and diatom mud dominate the upper half of the section, which is dated as Quaternary to Late Miocene in age (Hayes and Frakes, 1975). In the lower half, which is late Miocene to early Miocene and Oligocene in age, diatoms are absent but calcareous nannofossils are found in trace amounts. Similar to DSDP Site 268, there is a transition in facies at DSDP Site 269 from more distal facies in the lower part of the core to more proximal facies near the surface. Piper and Brisco (1975) interpret this facies change as resulting from substantial increased supply of sand and coarse silt and clay from the Antarctic continent, possibly in response to prograding of the continental margin.

5.3.3. The Inferred Long-Term Record of Glaciations

Investigators interpret the WL-U3 unconformity as having been eroded during the first grounding of an ice sheet on the continental shelf (Tanahashi et al., 1994; Eittreim et al., 1995; Escutia et al., 1997; Escutia et al., 2005), either about 40 m.y. ago (Eittreim et al., 1995) or 33.4–30 Ma (Escutia et al., 2005) (Table WL-2). Above WL-U3, early glacial strata (e.g. likely glacial outwash deposits) were provided by fluctuating temperate glaciers, and were deposited as low-dip-angle prograding foresets. The increase in stratal dips across unconformity WL-U8 in the prograding wedge at the shelf edge is interpreted to record a glacier-regime change from intermittent fluctuating glaciers to persistent oscillatory ice sheets, either on the Late Miocene (Escutia et al., 2005) or about 3 Ma (Rebesco et al., 2006) (Table WL-2). The steep foresets above WL-U8 likely consist of ice proximal (i.e. waterlain till and debris flows) and open-water sediments deposited as grounded ice sheets

Table WL-2: Continental shelf and rise stratigraphy and inferred East Antarctic Ice Sheet evolution in the Wilkes Land margin and timing of events.

Regional unconformities/ sesmic units	Timing of glacial events	Wilkes Land glacial
WL-S9	Pliocene-Pleistocece latest Miocene (?)	Persistent but oscillatory? Ice sheet
WL-U8	Pliocene (3 Ma) to mid-late Miocece (10–14 Ma)(?)	Transition from a dynamic to a persistent ice sheet
WL-S8	late Miocene (?)	
WL-U7		
WL-S7	early Miocene (?)	
WL-U6		Dynamic ice sheet
WL-S6	middle Miocene (?)	
WL-U5		
WL-S5	early Miocene (?)	
WL-U4		
WL-S4	late Oligocene-early Miocene	First arrival of an ice sheet
WL-U3	early Oligocene (33.5–30 Ma) (?)	to the coast
	early Oligocene to late Cretaceous	Ice Free

Source: Modified from Escutia et al. (2005).

extended intermittently onto the outer shelf – similar to sediments recovered from ODP Site 1167 on the Prydz Trough fan (O'Brien et al., 2001).

On the continental rise, the up-section increase in the energy of the depositional environment in units WL-S5 to WL-S7 (i.e. seismic facies indicative of proximal turbidites and of bottom-contour-current deposition) likely resulted from enhanced shelf progradation. Maximum rates of sediment delivery to the rise appear to have occurred during the development of units WL-S6 and WL-S7, which is inferred to have been during the Miocene (Hayes and Frakes, 1975; De Santis et al., 2003; Escutia et al., 2005). During deposition of WL-S8 and WL-S9, sediment supply to the lower continental rise decreased and depocentres shifted landward to the base of the slope and outer shelf (Escutia et al., 2002; De Santis et al., 2003; Donda et al., 2003; Escutia et al., 2005; Rebesco et al., 2006). Inferred age for Units WL-S8 and WL-S9 is Pliocene to Recent (De Santis et al., 2003). Sequence WL-S9 was deposited under a polar regime with a persistent ice sheet during the Pliocene–Pleistocene. At that time, most sediment delivered to the margin was trapped on the outer shelf and slope, forming steep prograding wedges, with some sediment bypassing the slope in channelized turbidity currents (Escutia et al., 2002; De Santis et al., 2003; Escutia et al., 2005).

During the Holocene open-water interglacial thick sections of diatom mud and oozes are deposited in deep inner shelf basins (Costa et al., 2007). These sediments hold an ultra-high-resolution record of climate variability likely by solar and ENSO forcing.

5.4. Prydz Bay (P. O'Brien and G. Leitchenkov)

Prydz Bay is a re-entrant in the East Antarctic margin, and overlies a rift structure that extends about 500 km into the interior of the continent. The rift has channelled drainage at least since the Early Cretaceous (Fig. PB-1; Arne, 1994) and presently controls the Amery Ice Shelf drainage system, which drains more than 16% of East Antarctica. This drainage basin includes the Gamburtsev Mountains, a subglacial range in which the Cenozoic ice sheet may have nucleated. Its long history, thick sediment and Cenozoic outcrops in the flanking Prince Charles Mountains have made Prydz Bay a likely site for preserving palaeo-climate records. Seismic surveys by Australia, Russia, Japan and the US and two ODP Legs 119 and 188 (Fig. PB-1), plus field studies and exposure dating, have provided an extensive picture of palaeo-climate evolution of the region.

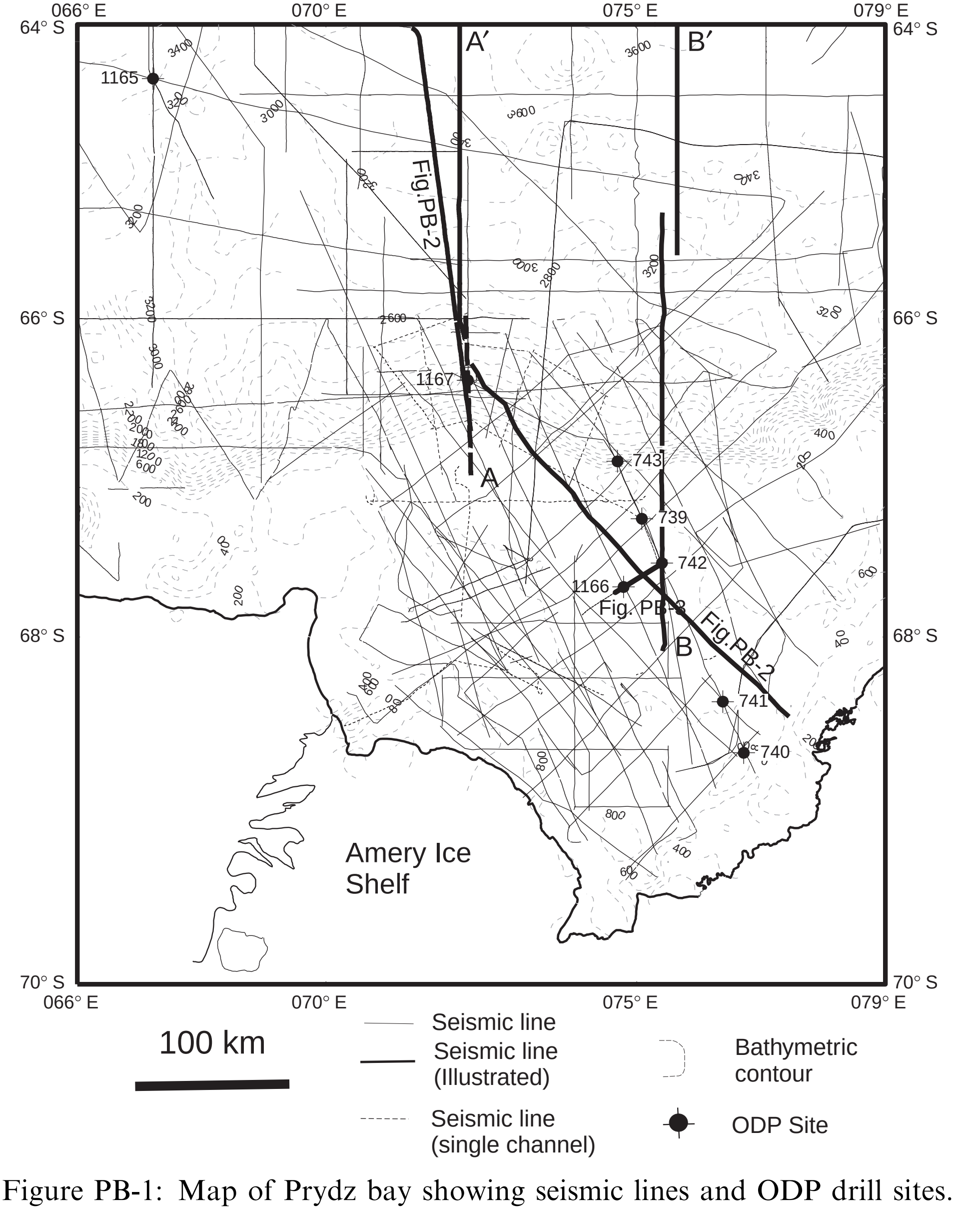

Figure PB-1: Map of Prydz bay showing seismic lines and ODP drill sites. Seismic lines illustrated in this chapter are in heavy black line. Foldouts are sections for A-A′ and B-B′.

5.4.1. Pre-Ice-Sheet (Pre-Late Eocene)

The Lambert Graben and Prydz Bay basin formed during the Carboniferous or Permian (Arne, 1994; Lisker et al., 2005) and were depocentres in pre-ice-sheet times. Seismic data from the Prydz Bay shelf show pre-ice-sheet sequences of parallel, moderately continuous reflectors (Figs. PB-2 and PB-3). ODP Sites 740, 741 and 1166 penetrated pre-ice-sheet sediments that were deposited in fluvial to fluvio-deltaic environments. ODP Site 740 intersected interbedded sandstone, siltstone and mudstone with reddish coloration (Shipboard Scientific Party, 1989), interpreted as fluvial flood plain deposits (Turner, 1991). The red coloration suggests a seasonal fluctuating rainfall regime but the age of this unit remains unknown (Truswell, 1991). It could be as old as Triassic, based on the presence of Triassic sediments in the northern Prince Charles Mountains (Leitchenkov, 1991; McLoughlin and Drinnan, 1997a, b). However Leitchenkov (1991) identified a thick (up to 5 km), faulted and high-velocity (up to 5.2 km/s) unit on multichannel data underlying these red beds. This sequence predates the main phase of breakup-related crustal extension, leading him to correlate the deep unit with Permian-Triassic sediments of the northern Prince Charles Mountains (Leitchenkov, 1991). If so, then the red beds in ODP Site 740 are likely Early Cretaceous or Late Jurassic in age.

ODP Sites 741 and 1166 intersected Cretaceous sediments beneath the Cenozoic section. The Cretaceous comprises interbedded dark siltstone and

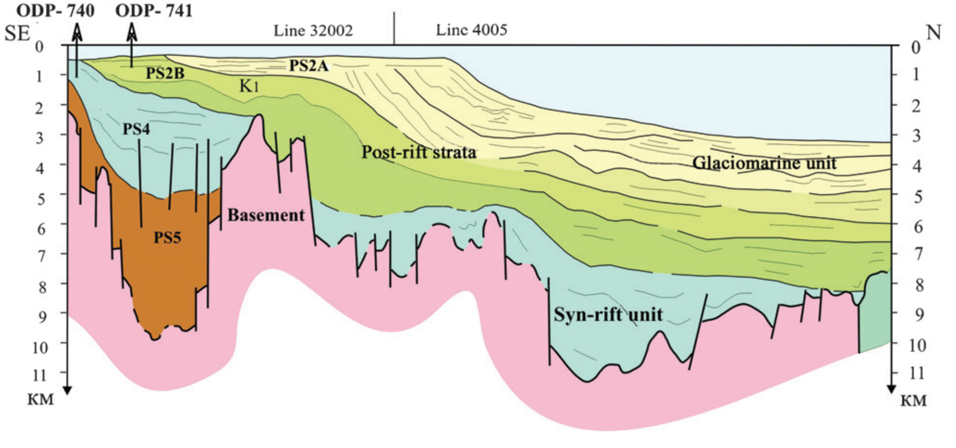

Figure PB-2: Diagramatic section across Prydz Bay shelf and slope based on Russian seismic lines SAE 32002 and RAE 4005. K1 are Cretaceous sediments. Location shown in Fig. PB-1.

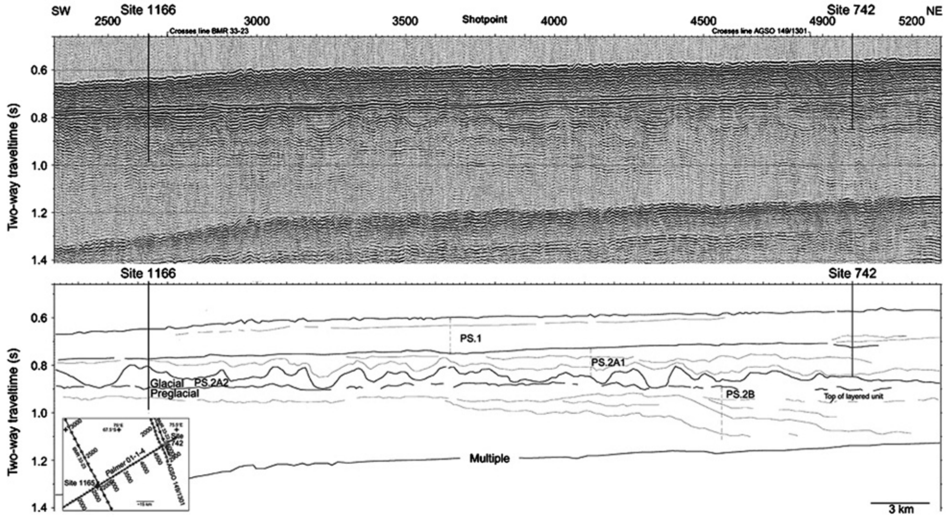

Figure PB-3: Seismic section between ODP sites 742 and 1166. Sequence PS2A2 comprises fluvio-deltaic sands of late Eocene age. Sequence PS2A1 overlies an erosion surface and comprises late Eocene marine muds with lonestones. Location shown in Fig. PB-1 (modified from Erohina et al., 2004).

sandstone with minor coal of probable delta plain to lagoonal origin. The ODP Site 1166 section is Turonian-Santonian(?), whereas ODP Site 741 recovered an older section of middle Aptian sediment (Fig. PB-3). Macphail and Truswell (2004) describe the palynomorphs from ODP Site 1166, and interpret the assemblage as indicating a conifer-dominated woodland vegetation, consistent with a cool, humid climate.

The continental rise seaward of Prydz Bay contains up to 5 km of post-rift sediments (Figs. PB-2, Foldouts PB-1 and PB-2; Mizukoshi et al., 1986, Stagg et al., 2004a, b). The lowermost seismic stratigraphic unit has parallel, mostly continuous reflectors typical of deep-ocean deposition that probably occurred during pre-ice-sheet times (Mizukoshi et al., 1986; Kuvaas and Leitchenkov, 1992; Kuvaas et al., 2005).

5.4.2. Early Glacial (Late Eocene)

In Prydz Bay, ODP Sites 739, 742 and 1166 recovered sediments deposited immediately before major glaciation (Barron et al., 1991; Cooper and O'Brien, 2004). The lithologies vary from dark siltstones to poorly sorted sands and bedded mudstone with lonestones. Seismic sections show that the sands overlie an undulating erosion surface, suggesting a period of erosion, possibly related to a relative low stand of sea-level (Erohina et al., 2004, Fig. PB-3). The sand unit fines up-section into the mudstone, which contains lonestones, marine diatoms and dynocysts (Shipboard Scientific Party, 2001a). Strand et al. (2003) interpret the sand unit as a fluvial to delta plain channel deposit. They found sand-grain surface textures that suggest erosion and breakage by glaciers, implying the presence of at least valley glaciers in the hinterland of Prydz Bay. The overlying mudstone with lonestones suggests a marine transgression, with floating ice as a feature of the resulting shallow embayment.

Macphail and Truswell (2004) report palynomorphs in the fine-grained units that indicate a late Eocene age (middle *Nothofagites asperus* zone), representing an age range from 33.9 to 39.1 Ma. This age overlaps with the age suggested by diatoms in the transgressive mudstones (33–37 Ma, Shipboard Scientific Party, 2001a). Macphail and Truswell (2004) also propose that the palynological assemblage was derived from a flora similar to stunted *Nothofagus* rainforest scrub, and consisted of ground-hugging plants and canopy trees about 1 m high. Today, such floras occur outside of Antarctica at higher altitudes, where cool temperatures limit tree growth. Therefore, the Prydz Bay flora reflects a cool to cold environment at sea-level. More precise temperature estimates are not possible because the plants present were tolerant of a wide range of conditions (Macphail and Truswell, 2004).

5.4.3. Ice-Sheet Development (Oligocene–Miocene)

The older glacial section of the shelf comprises tabular units that pinch out shoreward due to inner-shelf erosion, and that extend seaward into prograding slope deposits (Cooper et al., 1991a). Palaeo-shelf edges for these units are better defined up-section as foreset strata steepen seaward (Fig. PB-2, Foldout PB-1). Shelf drilling (ODP Sites 739, 740, 741, 742 and 1166) recovered probable subglacial and glacimarine diamicts, with thin interbedded diatomaceous mudstones deposited during warm episodes (Hambrey et al., 1991; Erohina et al., 2004). The drilling and seismic evidence indicates glacial advance well across the Prydz Bay shelf during cold episodes, probably reaching the shelf edge. Over-compacted horizons indicate periods of glacial erosion and ice loading during the early Oligocene, Miocene and Plio-Pleistocene (Solheim et al., 1991; Shipboard Scientific Party, 2001a). Before the late Miocene, the Prydz Bay shelf prograded uniformly across its width, with the bulk of the ice and entrained sediment coming from the southern end of the bay (i.e. from the Lambert Graben). The Prydz Bay continental slope became progressively steeper from the early phase of glaciation in early Oligocene time, to reach angles of as much as 8° on the present slope (Foldouts PB-1 and PB-2).

On the continental rise, a pre-ice-sheet unit is overlain by one exhibiting channel-levee geometries. The nature of the change in geometry and the tracing of reflectors to the shelf drilling suggest that this change originated from the glacial expansion and increased sediment supply in the early Oligocene (Kuvaas and Leitchenkov, 1992). Overlying the channel-levee complexes are sequences that include thick mounds and sediment waves suggestive of contourite deposition, in addition to turbidite channels and associated levees formed by intensified down-slope and along-slope currents in the early Miocene (Fig. PB-2, Foldout PB-2).

ODP Site 1165 (Leg 188) drilled 999 m with 69% recovery into a thick mound of lower Miocene and younger contourite sediments with turbidites only in the upper 5 m (Cooper and O'Brien, 2004). The hole penetrated the base of the mounded sequences, which was still of early Miocene age (Handwerger et al., 2004). The drilling confirmed the seismic interpretation that deposition of the thick contourite mounds had commenced by at least early Miocene time, but sediments above and below the surface were typical contourites – fissile claystones with abundant silt laminae (Handwerger et al., 2004). Therefore, there was no obvious lithological change in the hole to suggest a reason for the change from low relief submarine fans to highly mounded deposits, previously inferred to be mixed turbidite-contourites.

ODP Site 1165 intersected a surface that can be mapped along the rise, and that marks a middle Miocene (14–16 Ma) change in sedimentation from laminated contourites to hemipelagic and pelagic facies (Cooper and O'Brien, 2004). Also, minerals and fossils recycled from shelf deposits first appear, suggesting the start of intense erosion by ice and overdeepening of the shelf. At this time, sedimentation rates slow more rapidly at the drill site, falling from 100 m/m.y. in the early Miocene to 37 m/m.y. in the mid-Miocene to 10 m/m.y. during the Plio-Pleistocene (Shipboard Scientific Party, 2001c; Florindo et al., 2003; Fig. PB-4).

On shorter time scales, Grützner et al. (2003) examine the proportions of terrigenous sediment and biogenic opal in ODP Site 1165 between 3.4 and 7.6 Ma. They find high opal content from 5.8 to 5.2 Ma, which they relate to reduced sea ice and increased productivity. They also identify terrigenous intervals with high sedimentation rates from 7.2–6.6 Ma and 5.2–4.8 Ma, which they interpret as indicating high erosion rates and a fluctuating ice sheet under the influence of obliquity forcing. Grützner et al. (2003) also report cyclic variations in sediment composition and physical properties that have

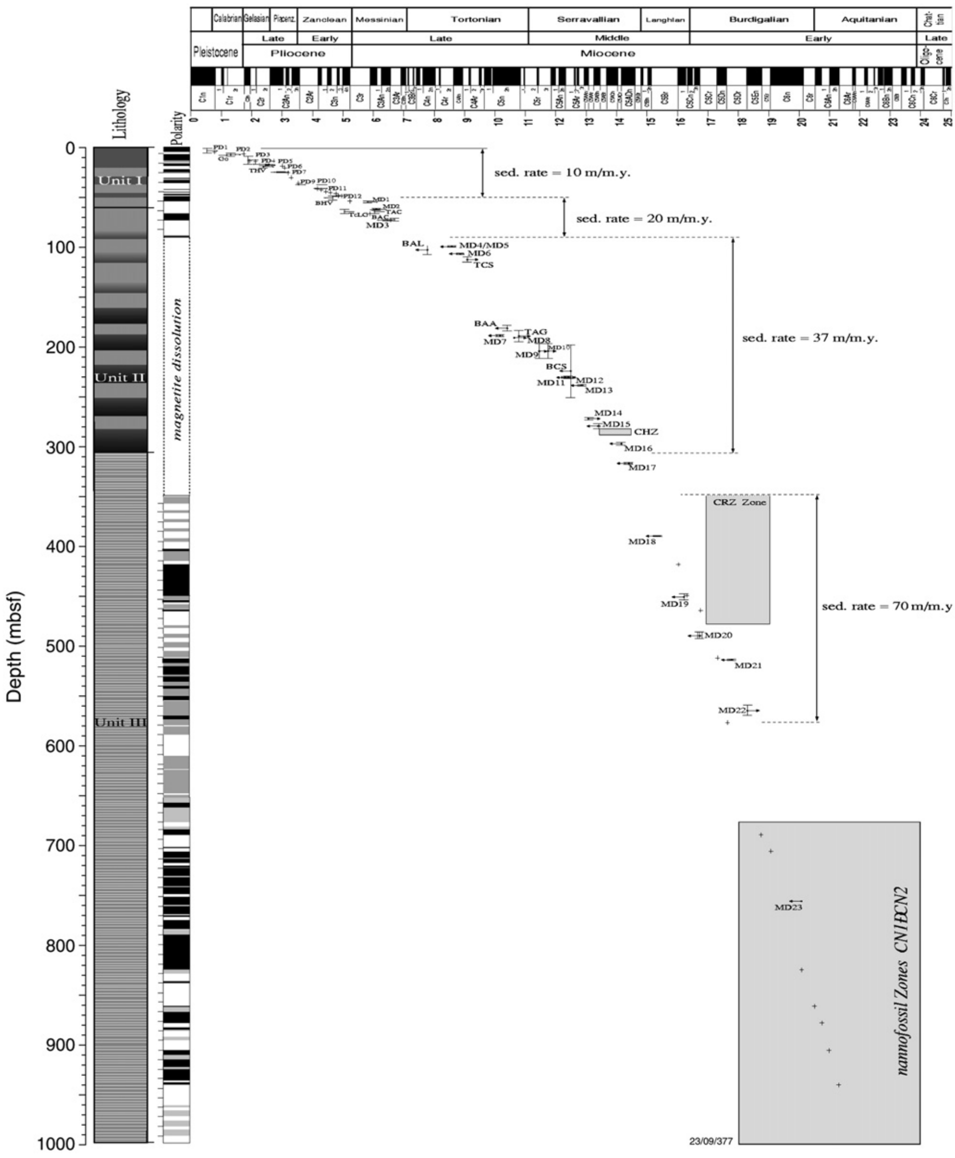

Figure PB-4: Age-depth model for ODP Site 1165 from Shipboard Scientific Party (2001c) showing rapid sedimentation during the early Miocene, reducing rapidly through the late Miocene to Pliocene.

spectral peaks at ~94, 41, 31, 21, and 18 k.y. cycles. Williams and Handwerger (2005) report that geophysical log parameters detect cycles of biogenic and terrigenous input at periods of ~15–23 and ~135 k.y., probably representing Milankovich-scale forcing of paleoenvironmental processes. Uncertainty in the age model of the hole prevents them from exact matching of peaks.

5.4.4. The Polar Ice Sheet (Late Miocene(?)–Pleistocene)

In the early Pliocene, ice flow regimes changed and ice was focused into an ice stream on the western side of the bay, cutting a cross-shelf trough, the Prydz Channel. The ice stream delivered basal debris to the shelf edge, where the debris built a trough mouth fan on the upper continental slope (Prydz Channel Fan, O'Brien and Harris, 1996; O'Brien and Leitchenkov, 1997; O'Brien et al., 2004). On the banks adjacent to Prydz Channel, vertical aggradation of subglacial debris produced tabular units while glacial erosion overdeepened the inner shelf.

Two ODP holes were drilled into the continental slope. ODP Site 743 was drilled to 98 mbsf into the eastern, steep part of the slope, and recovered diamict. ODP Site 1167 was drilled to 447.5 mbsf into the Prydz Fan, and recovered muddy, pebbly sands and diamicts deposited by slumping of subglacial debris interpreted to have originated at the ice grounding line at the shelf edge (Foldout PB-2, O'Brien et al., 2001; Passchier et al., 2003). ODP Site 1167 also recovered thin mudstone units deposited during periods of reduced ice extent (Shipboard Scientific Party, 2001b, Passchier et al., 2003). More than 90% of the fan was deposited before the mid Pleistocene, and there were only three advances of the Amery Ice Shelf to the shelf edge in the late Pleistocene (O'Brien et al., 2004). Clay mineralogy, magnetic properties and clast composition at ODP Site 1167 show changes suggesting that the Pleistocene peak of erosion and ice volume in the Lambert-Amery drainage system occurred in the early Pleistocene (O'Brien et al., 2004). Oxygen isotope measurements on foraminifera from ODP Site 1167 also suggest that sedimentation was reduced after the mid-Pleistocene, with the last ice advance to the shelf edge at about Marine Isotope Stage 16 (612–698 ka; Lisiecki and Raymo, 2005). However, the stratal record is fragmentary because hiatuses are common, which leads to a tentative identification of isotope stages (Theissen et al., 2003). During the mid-to-late Pleistocene, ice advances were less extensive. During the last glacial cycle, the Amery Ice Shelf grounded only 100 km north of the present ice shelf edge and far from the continental shelf edge (Domack et al., 1998; O'Brien et al., 1999) (Fig. PB-1).

On the continental rise, sedimentation rates decreased through the Pliocene and Pleistocene because less detritus was eroded from the continent and because sediment was deposited on the upper slope in front of the Prydz Channel. The inferred early Pliocene base of the Prydz Channel Fan is the prominent unconformity mapped by Mizukoshi et al. (1986, Reflector A) and O'Brien et al. (2004, Reflector PP-12).

Drilling and seismic evidence indicate that glaciers advanced to the edge of the Prydz Bay shelf in cold episodes during the Pliocene and early Pleistocene, yet evidence of warm episodes also exists. Sediments in the Prince Charles Mountains indicate open-water fjordal environments in the Miocene to Pliocene (Hambrey and McKelvey, 2000; Whitehead et al., 2003, 2004). Lower Pliocene marine diatomite in the Vestfold Hills, on the eastern side of Prydz Bay, contains evidence of temperatures 4°C warmer than today (Whitehead et al., 2001). ODP Site 1167 includes a thin mudstone horizon at 217 mbsf with calcareous nannoplankton not presently found in Prydz Bay (Shipboard Scientific Party, 2001b), suggesting warmer conditions at about 1.1 Ma (Pospical 2004; Lavelle, personal communication, 2001). These occurrences indicate warmer episodes when the Amery Ice Shelf edge retreated several hundred kilometres inland from its present position, and warmer water intruded Prydz Bay.

5.4.5. Prydz Bay Summary

Seismic interpretation and drilling data reveal that the glaciation of Prydz Bay started in the latest Eocene. At that time, Prydz Bay was occupied by a fluvio-deltaic plain covered with stunted cool-temperate vegetation. Rivers flowing through the Lambert Graben were fed by glaciers in the hinterland. The sea transgressed across the plain and floating ice delivered dropstones to the shallow embayment. The embayment became glaciated in the early Oligocene, with ice-sheet-scale glaciers depositing subglacial till, and glacimarine diamicts when the ice was not grounded. The ice was probably wet-based. In the early Miocene, a large temperate to polythermal ice sheet advanced and retreated across the embayment, supplying large quantities of detritus to the continental rise, where the detritus was deposited in large mounds.

The mid-Miocene was marked by the start of a cooling trend and the development of a thicker, colder and more erosive ice sheet. Shelf over-deepening began, but progressively less detritus was delivered to the continental rise. In the early Pliocene, ice flow became concentrated on the western side of the bay in an ice stream that deposited sediment in a trough mouth fan. During warm phases, open-water extended landward as far as the northern Prince Charles Mountains. Ice volumes and depths of erosion reached a peak in the mid Pleistocene and the cold, polar ice sheet was established. The Amery Ice Shelf no longer grounded at the shelf edge in Prydz Channel during glacial episodes.

5.5. Weddell Sea (Y. Kristoffersen and W. Jokat)

The principal features in the Weddell Sea sector relevant to resolving the Antarctic paleoclimate and paleoceanographic history are prograding wedges of glacigenic sediments along the entire margin, a major trough-mouth fan (Crary Fan), and numerous sediment drifts on the slope and in the deep basin, particularly along the western and northwestern side of the Antarctic Peninsula. Ice sheet flow-line patterns suggest that the continental margin of the eastern and southern Weddell Sea east of 45°W receives drainage from the EAIS, whereas the continental margin west of 45°W receives drainage from the WAIS (Fig. WS-1).

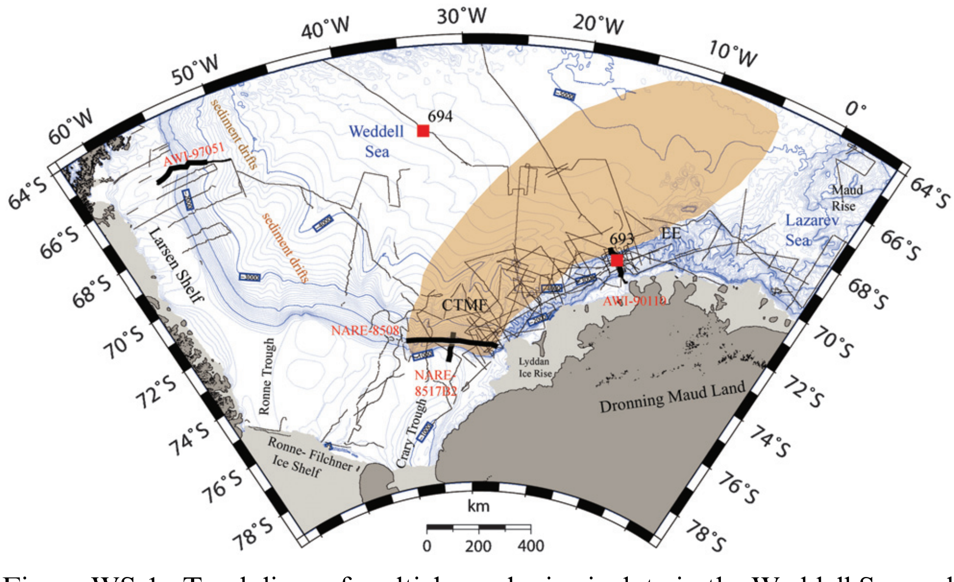

Figure WS-1: Track lines of multichannel seismic data in the Weddell Sea and locations of ODP drill sites. Bathymetry after Schenke et al. (1998). Areal extent of proximal and distal deposits of the Crary Trough Mouth Fan are outlined by light brown shaded area. True extent of sediment drifts in the southwestern and western Weddell Sea is poorly defined due to lack of data coverage. CTMF, Crary Trough Mouth Fan; EE, Explora Escarpment.

5.5.1. The Regional Seismic and Geologic Database

Modern geophysical data in the Weddell Sea comprise about 45,000 km of MCS lines from surveys principally by German, Norwegian and Russian research institutions since 1976 (Fig. WS-1). ODP drilled four sites in the Weddell Sea during ODP Leg 113, and ODP Site 693 on the Dronning Maud Land continental slope has been the most useful for stratigraphic calibration (Figs. WS-1 and WS-2). Prior to the deep drilling, stratigraphic studies in the region were conducted by Elverhøi and Maisey (1983), Hinz and Krause (1982), Hinz and Block (1984), Haugland et al. (1985) and Hinz and Kristoffersen (1987). Correlations with ODP Site 693 were made by Miller et al. (1990), Kuvaas and Kristoffersen (1991), Moons et al. (1992), Michels et al. (2002) and most extensively by Rogenhagen et al. (2004) (Fig. WS-2).

5.5.2. Acoustic Stratigraphy of the Shelf/Slope/Rise Environment-Spatial and Temporal Characteristics

The continental shelf of the Weddell Sea is characterized by a prograding wedge of glacigenic sediments more than 1 km thick below the shelf edge (Fig. WS-3). The wedge downlaps onto older units, which are characterized by rather uniform thickness in the down-slope direction (Fig. WS-3a). Wedge deposition is a first order result of massive transport of unsorted texturally immature sediments by advance of a grounded ice sheet to the shelf edge (Barker et al., 1998). The acoustic response of coarse sediment in proximal positions below the shelf and uppermost slope is one of discontinuous reflection events. Continuity and definition of acoustic stratification improve in the down-slope direction as a result of progressive sorting and increased relative abundance of finer material. The shelf edge may appear rectilinear, but the three-dimensional wedge architecture in the eastern Weddell Sea reveals an amalgation of adjacent small discrete cones of glacial sediments sourced by smaller ice streams (Kristoffersen et al., 2000). The spectrum of cones reflects broad scale expansion of the EAIS, but adjacent cones may or may not be coeval. Topsets of the prograding wedge are generally truncated at the seabed. Shelf aggradation is indicated in the southern Weddell Sea west of the Crary Trough, but the vast shelf area west of 45°W has not been accessible for seismic surveys (Fig. WS-1).

The maximum thickness of prograding units below the mouth of the Crary Trough and also below the shelf north of Lyddan Ice Rise is more than 3 km (Rogenhagen et al., 2004). ODP Site 693 (Fig. WS-2) provides local

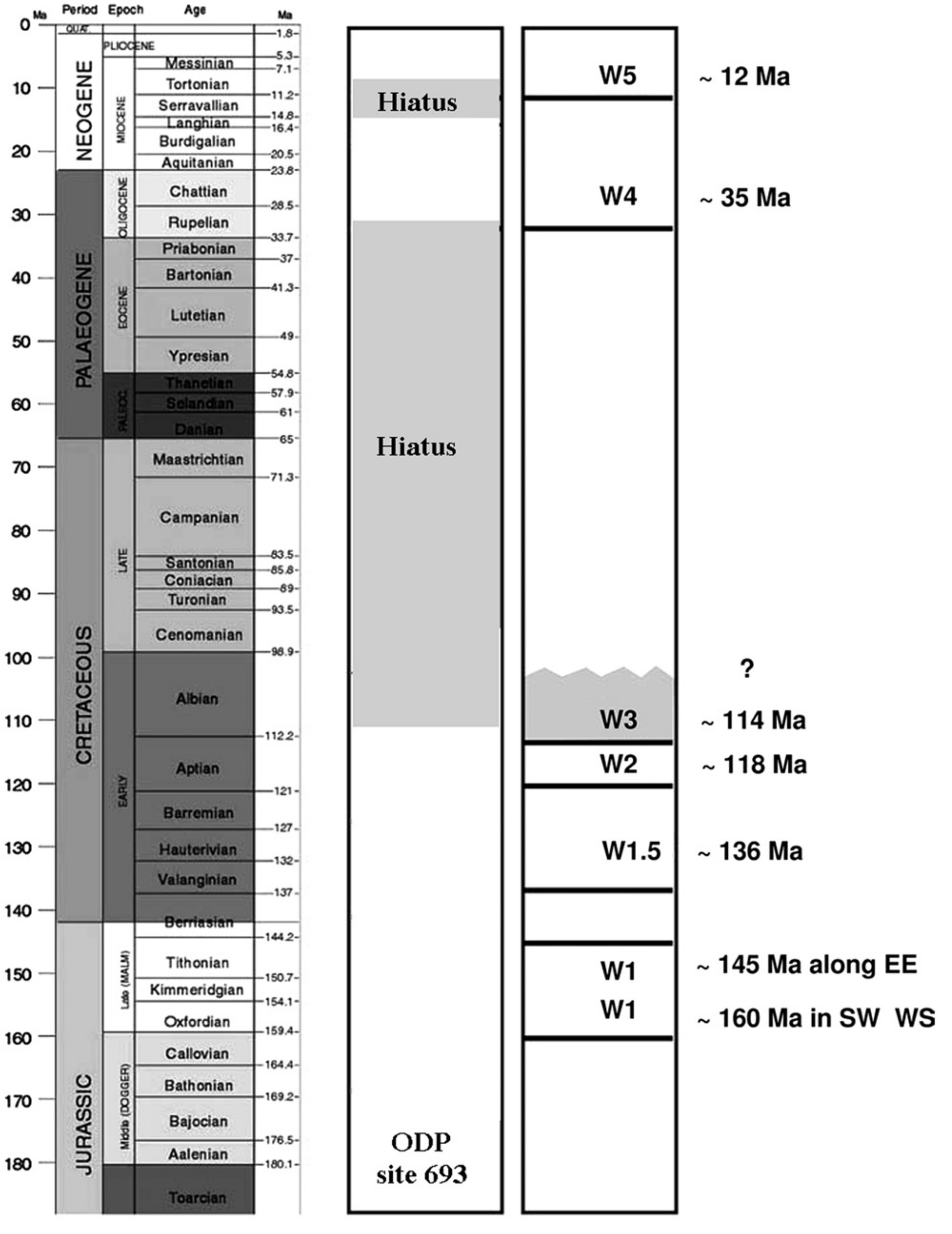

Figure WS-2: Stratigraphic summary column. Modified from Rogenhagen et al. (2004).

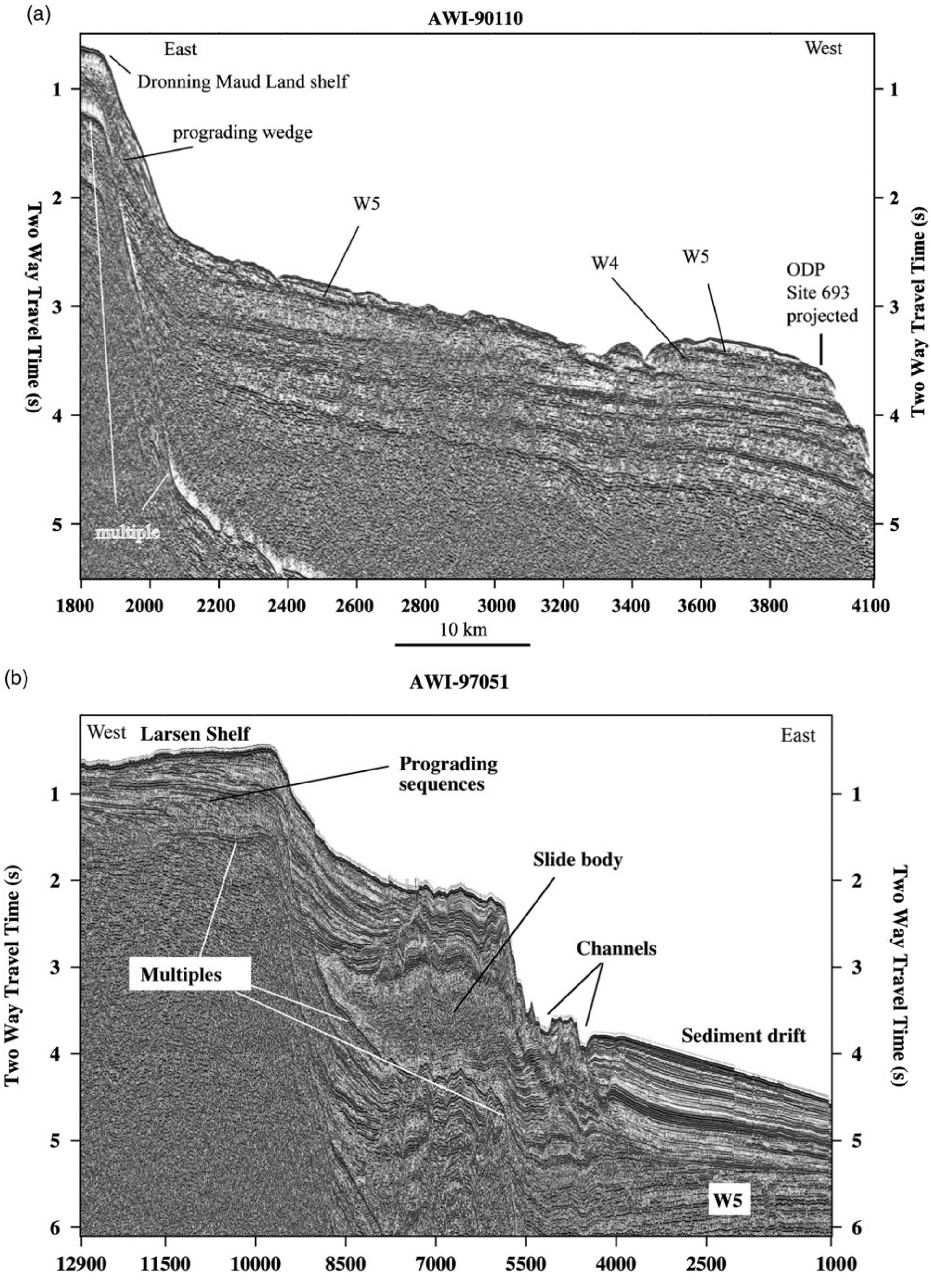

Figure WS-3: (a) Seismic line AWI-90110 across the Dronning Maud Land margin showing the prograding wedge (modified from Michels et al., 2002). (b) Seismic line AWI-97051 across the Larsen Shelf and Slope, showing the prograding shelf and sediment drift on the lower continental slope (modified from Michels et al., 2001). Profile locations are in Fig. WS-1.

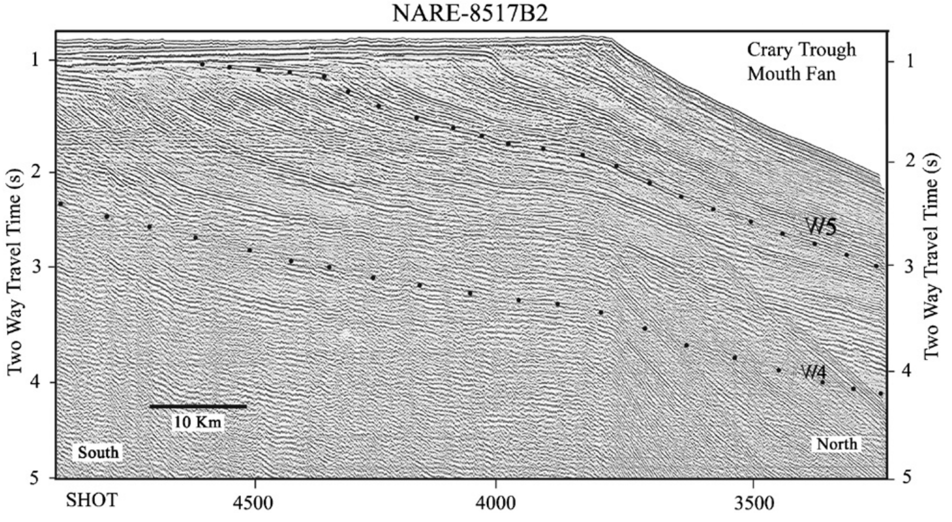

Figure WS-4: Seismic line NARE-8517 across the prograding Crary Trough Mouth Fan (modified from Kuvaas and Kristoffersen, 1991). Profile location is in Fig. WS-1.

calibration of the acoustic section (Miller et al., 1990), but regional extrapolations are inhibited along-slope by numerous canyons, and are inhibited down-slope by the steep Explora Escarpment (Fig. WS-1). The Crary Fan, a regional feature at the mouth of the Crary Trough, is associated with large channel/levee complexes, which extend up to 1,000 km to the north into the basin (Figs. WS-1, WS-4 and Foldout WS-1). Initial fan evolution is correlated with the resumption of sediment deposition above an Albian-early Oligocene hiatus at ODP Site 693 (Reflector W4).

Sediment drifts are common within the Neogene stratigraphic interval along the continental slope (Fig. WS-1) in the western Weddell Sea (Michels et al., 2001; Maldonado et al., 2005).

5.5.3. The Weddell Sea Pre-Ice-Sheet Depositional Environment

Acoustic stratigraphic information on the shelf is limited to subbottom depths comparable to the local water depth due to severe multiple reflections (e.g. Fig. WS-3). The pre-ice-sheet Cenozoic shelf edge was more than 10 km landward of its current position along the Dronning Maud Land continental margin (Kristoffersen et al., 2000), and 70 km to the south (Fig. WS-4) in the southern Weddell Sea (Kuvaas and Kristoffersen, 1991). The shoreward shift in the western Weddell Sea is unknown. The deeper strata below the continental slope (i.e. below W4) appear unstructured throughout. The older sediments are thickest (5–8 km) below the Larsen Shelf in the western Weddell Sea (Rogenhagen and Jokat, 2000), and may be up to 15 km thick along the front of the Ronne and Filchner Ice shelves (Leitchenkov and Kudryavtzev, 2000). In the central Weddell Sea Basin, the pre-Oligocene section of inferred turbidites is more than 1 km thick, and thins by basal onlap towards the margins to less than 0.5 km (Rogenhagen et al., 2004). High seasonal variations in sea-surface temperatures and a well-developed seasonal thermocline characterized the early Paleogene Weddell Sea (Kennett and Barker, 1990). On Maud Rise, siliceous biogenic facies began to replace carbonate facies during the latest Eocene-earliest Oligocene (Kennett and Barker, 1990). A possible early Cenozoic seaway between East and West Antarctica could have been up to 700 m deep, and may have persisted into the Oligocene if no WAIS was present (Lawver and Gahagan, 2003). At ODP Site 693 on the middle continental slope, middle lower Oligocene and younger glacial sediments are separated by a hiatus from Albian radiolarian diatomite and claystones (i.e. Reflector W4). The unconformity may represent non-deposition and/or mild erosion (Kennett and Barker, 1990).

5.5.4. Change from Non-Glacial to Glacial Conditions

Sediment fluxes on high latitude continental margins are closely connected to climate extremes. In the Weddell Sea, environmental change is manifested by a basin-wide change in acoustic character within the sedimentary section (Reflector W4) at about 1 s TWT below the sea bed (Rogenhagen et al., 2004). Younger deposits in the basin have finely laminated continuous acoustic stratification, and geometries on the slope are in the form of channel/levee complexes over a wide range of spatial scales. The change in depositional environment is interpreted to have originated from an increased sediment flux, caused by increased erosion of the continent and increased down-slope transport. At ODP Site 693 on the middle continental slope, the acoustic change correlates stratigraphically with resumed preservation of lower Oligocene sediments. The deposits include rounded dropstones in lower Oligocene (32–33 Ma) diatom muds, a signal of the first presence of glaciers on the adjacent parts of East Antarctica (Kennett and Barker, 1990). Subsequent early Miocene sedimentation rates at this site were low (7 m/Ma). A more dramatic change in sediment flux to the margin is documented by a threefold increase in sedimentation rate (to 24 m/m.y.), when sedimentation resumed following a hiatus that spanned the middle Miocene. Increased sediment input is related to expansion of ice on the East Antarctic continent. The hiatus at ODP Site 693 correlates with a regional acoustic reflection event (W5) identified below the continental slope and rise along the entire Weddell Sea margin (Rogenhagen et al., 2004). Shelf progradation accelerated dramatically along the eastern and western margins of the Weddell Sea (Fig. WS-3), with grounded ice extending to the shelf edge in the late Miocene (Michels et al., 2001; Michels et al., 2002). A range of contourite drifts formed on the slope and rise in the northwestern Weddell Sea (Michels et al., 2001; Maldonado et al., 2005). Sedimentation rates at ODP Site 693 reached 60 m/m.y. in the early Pliocene, and subsequent Quaternary sedimentation rates were reduced to 16 m/m.y. (Gersonde et al., 1990). Sediment input to the margin in the southeastern Weddell Sea was focused toward a trough mouth fan. The Crary Fan began to expand at the time of change to a glacial environment (above Reflector W4, Fig. WS-4 and Foldout WS-1), and major channel/levee complexes evolved in three phases. The last of these three phases (Reflector W5, Fig. WS-4 and Foldout WS-1) was from the late Miocene on (Kuvaas and Kristoffersen, 1991; Moons et al., 1992).

5.5.5. The Glacial/Interglacial Environment

The change from a glacial to an interglacial environment was associated with major changes in sediment flux. Average sediment deposition on the eastern Weddell Sea margin (10°W) during the last two climatic cycles (300 k.y.) varies from 5 cm/k.y. on the upper slope to over 1 cm/k.y. on the lower slope (Grobe and Mackensen, 1992). Sedimentation was most rapid during the beginning of interglacials, with rates on the middle slope four to five times higher than during glacials. We note, however, that the grounded EAIS only reached the mid-shelf in this area during the LGM (Kristoffersen et al., 2000). Sediment input in the southern Weddell Sea was focused in the Crary Trough Mouth Fan (Figs. WS-1, WS-4 and Foldout WS-1). The fan comprises large channel-levees on the flanks of deep-water channels, such as the Cold Water Channel and the Deutschland Channel (Foldout WS-1). Grounded ice reached the shelf edge at the trough mouth during the last glaciation (Bentley and Anderson, 1998), and deposition on the levees (in water depths of 2,000–3,000 m) ranged from 100–200 cm/k.y. during the LGM to a few cm/k.y. during the present interglacial (Weber et al., 1994). Episodic sediment transport into the basin also occurred by mass flows during interglacials, probably as partial collapse of the deposits on the upper continental slope. A 90-m-thick sandy turbidite unit was deposited within 0.5 m.y. during the early Gilbert Chron (4.8 Ma) at ODP Site 694 (Fig. WS-1), and may be the distal expression of mass wasting events on the continental slope in the southwestern Weddell Sea (Shipboard Scientific Party, 1988). Also, major early Pliocene drawdown of East Antarctic ice is postulated to have triggered extensive mass flows that originated from the Crary Trough Mouth Fan (Bart et al., 1999).

In the western Weddell Sea, upper Miocene and younger sediments (above Reflector W5) are mostly drift deposits that reach a thickness of more than 1 km below the middle slope, seaward of the Larsen Shelf (Rogenhagen and Jokat, 2000; Michels et al., 2001; Maldonado et al., 2005). Present and past bottom currents circulated in nearly the opposite direction to channel transport, and cross-channel flow was in the same direction as the Coriolis force acting on down-slope turbidity currents in the southern Weddell Sea. Sediments scavenged from turbid channel flow by cross-channel bottom currents sourced the benthic boundary layer and enhanced formation of sediment drifts along the western and northern Weddell Basin. The actual drift distribution was mainly controlled by the physiography of the basin and bottom current flow directions (Maldonado et al., 2005). These drifts represent a storehouse of paleoceanographic and climatic proxies not yet sampled by scientific drilling.

5.5.6. Continental Margin Sediments and Ice-Sheet History

The mass balance of the EAIS, the nature of the substratum and the continental topography, particularly in the coastal region, determine sediment input to the continental margin. Enhanced input of sediments to the continental margin at ODP Site 693 in the eastern Weddell Sea and development of a prograding wedge started in the latest Miocene and peaked during the earliest Pliocene (Gersonde et al., 1990). The seismic tie between ODP Site 693 and the southern Weddell Sea is uncertain, but Kuvaas and Kristoffersen (1991) suggest that fan development started in the southern Weddell Sea by the early Oligocene (above Reflector W4, Fig. WS-4 and Foldout WS-1), and that about two-thirds of the sediment thickness at the mouth of the present Crary Trough was already in place by the late Miocene (i.e. below Reflector W5). Channel-levee complexes have migrated eastward on the Crary Trough Mouth Fan, and late Miocene and younger deposition constructed a third major channel-levee complex and deposited about 1 km of sediments below the trough mouth (Fig. WS-4 and Foldout WS-1). These age relations imply that the principal input of sediments from East

Antarctica to the Weddell Sea margin from the early Oligocene to the late Miocene originated from a glaciated interior of the continent via the Crary Trough, and that there was effectively no input along the Dronning Maud Land margin. At this point, the significance of a local thickness maximum of glacial sediments north of Lyddan Ice Rise (Rogenhagen et al., 2004) is unclear. The EAIS expanded to the Dronning Maud Land margin during the latest Miocene–earliest Pliocene and formed a prograding wedge below the continental shelf and slope. Sea ice cover has prevented acquisition of the seismic data from west of 45°W and north of the Ronne Ice Shelf (Fig. WS-1) needed to study the depositional geometries of sediments originating from the catchment area of the WAIS. Data from this area also are needed to study the relation between eastern and western sediment source regions.

Moraine complexes on the shelf in the eastern Weddell Sea suggest that the EAIS was grounded on the mid-shelf and did not reach the shelf edge during the LGM (Kristoffersen et al., 2000), except at the mouth of the Crary Trough (Bentley and Anderson, 1998).

5.6. Antarctic Peninsula (R. Larter)

Cenozoic tectonic processes have diversely affected the Antarctic Peninsula region and its climate record. Hence, we separately discuss four main subregions.

5.6.1. The Eastern Margin

This subregion includes the Weddell Sea margin of the Antarctic Peninsula and Larsen Basin (Fig. AP-1). Persistent sea ice covers the region (Gloersen et al., 1992), hence relatively few research cruises have been conducted here. Macdonald et al. (1988) used regional geologic and aerogeophysical data to infer that a large Mesozoic–Cenozoic sedimentary basin extends ~700 km south from James Ross Island. Four main seismic stratigraphic units are identified from SCS reflection data on the shelf and upper slope (Anderson et al., 1992; Sloan et al., 1995; Fig. AP-2): Unit 4: acoustic basement interpreted as Jurassic and younger volcanic rocks; Unit 3: seaward-dipping reflections interpreted as Late Cretaceous to Oligocene marine shelf deposits, the older part of which are coeval with those on nearby Seymour Island; Unit 2: prograding sequences with truncated foresets that downlap onto Unit 3, and that are thought to have been deposited by multiple advances of grounded ice across the shelf in the Miocene and early Pliocene;

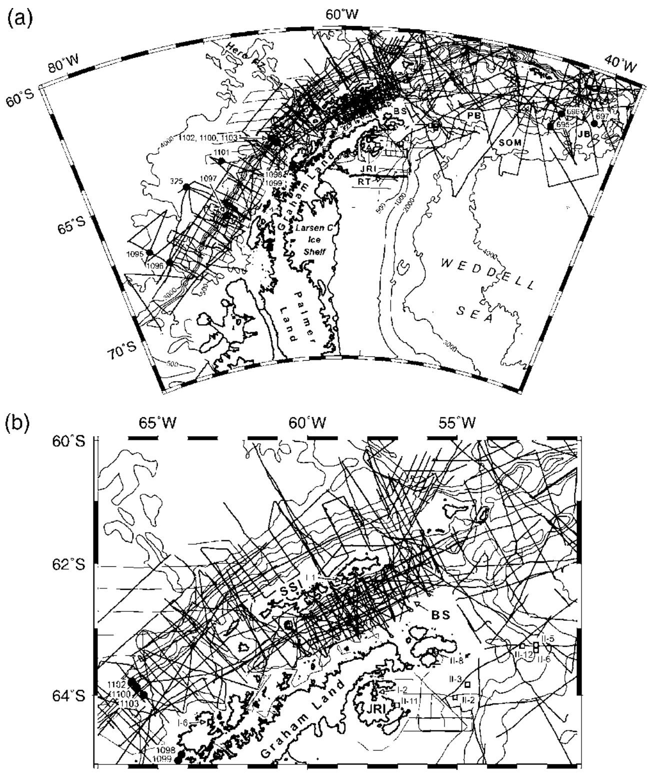

Figure AP-1: (a) Track lines of multichannel (thick lines) and single-channel (thin lines) seismic data in the Antarctic Peninsula region, DSDP and ODP drill sites (filled circles, annotated with site numbers) and SHALDRIL sites (open squares). SHALDRIL sites are only marked where either >10 m subseafloor penetration was achieved or pre-quaternary sediments were recovered. Bathymetric contours are at 1,000 m intervals down to 4,000 m, with 500 m contours included locally on the shelf. Bathymetric data are based on Smith and Sandwell (1997) east of the Peninsula and north of 62°S. Bathymetry for most of the area west of the Peninsula is from Rebesco et al. (1998), the exception being the 500 m contours in the southern Bellingshausen Sea, which are from Ó Cofaigh et al. (2005). To the east of the Peninsula, 500 m contours south of James Ross Island (JRI) are based on figures in Evans et al. (2005), and the 500 m contour north of James Ross Island is based on multibeam echo sounding data maps produced from data collected on RV *Nathaniel B. Palmer* Cruises 0003 and 0107. Bold line is location of seismic profile in Fig. AP-2. SOM: South Orkney Microcontinent; JB: Jane Basin; PB: Powell Basin; BS: Bransfield Strait; RT: Robertson Trough. (b) Expanded map of the northern Antarctic Peninsula with SHALDRIL site numbers labelled (I/II indicates first/second cruise). Same bathymetry contours shown as in (a), except 500 m contours around JRI omitted. SSI: South Shetland Islands.

Unit 1: aggrading reflections interpreted as deposits from fluctuating dynamic ice sheets in the Pliocene and Pleistocene.

MCS reflection data show at least 8 km of sediment at the base of the continental slope, overlying likely Early Cretaceous age basement (Barker and Lonsdale, 1991). The northern continental slope has plastered contourite drift deposits up to 900 m thick, thought to have been deposited by north-flowing glacially influenced bottom currents. Pudsey (2002) suggests that drift deposition began in the early Miocene at the onset of bottom water flow, or in the latest Miocene at the onset of volumnious glacially derived sediment supply to the western Weddell Sea.

Late Quaternary shelf sediments have been sampled by seafloor coring (e.g. Domack et al., 2001a, b, 2005; Pudsey and Evans, 2001; Pudsey et al., 2001; Brachfeld et al., 2003; Evans et al., 2005). These researchers infer that grounded ice converged into major ice streams and advanced to the shelf edge during the LGM, that the Prince Gustav Sound Ice Shelf collapsed and reformed in the mid-Holocene, and that the recent collapse of the Larsen B Ice Shelf is unprecedented during the Holocene. Recent drilling by the SHALDRIL project has obtained the first samples from older sequences (Shipboard Scientific Party, 2005, 2006; Anderson et al., 2006, 2007).

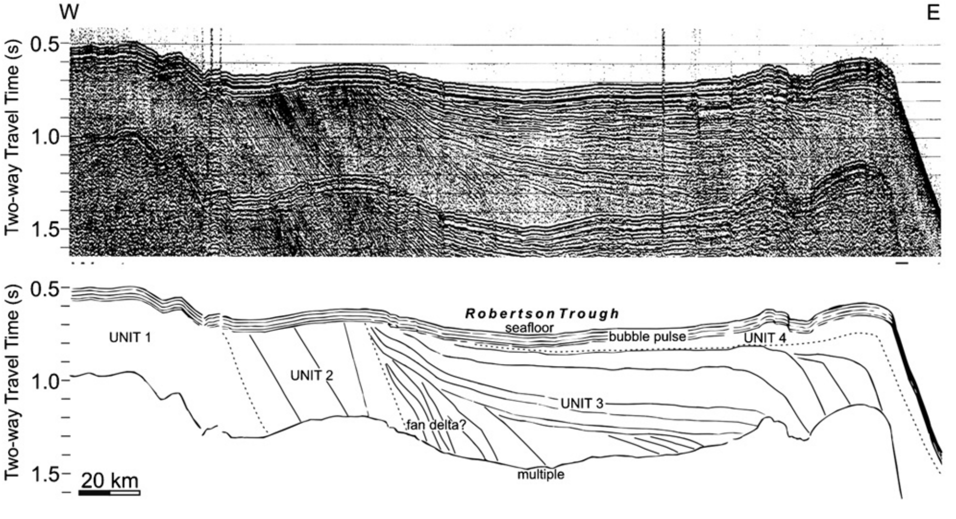

Figure AP-2: Single-channel seismic line across the eastern margin of the Antarctic Peninsula at 65°15′S, collected on RV *Nathaniel B. Palmer* in 1993. Line drawing interpretation shows the internal geometries and boundaries (dashed lines) between the main seismic units. Vertical exaggeration at the seafloor is 82:1. Adapted from Sloan et al. (1995). Line location is shown in Fig. AP-1.

Sequences drilled by SHALDRIL are principally shallow marine sands, sandy and silty muds, and pebbly muddy sands from neritic environments, with mollusc shells distributed throughout the cores. The cores are dated as: late Eocene to early Oligocene, Oligocene, middle Miocene, early Pliocene and Holocene.

5.6.2. The South Orkney Islands Region

This subregion includes the South Orkney Microcontinent (SOM) and the adjacent deep-water Jane and Powell basins (Fig. AP-1). The SOM extends about 350 km from east to west and 250 km from north to south, and is underlain by Mesozoic metamorphic and sedimentary rocks (Thomson, 1981; Dalziel, 1984). Offshore, the SOM includes four Cenozoic sedimentary basins (King and Barker, 1988) with up to 5 km of sediment (Harrington et al., 1972; Busetti et al., 2001, 2002). Powell Basin (up to 3,600 m deep) formed as the SOM rifted and drifted away from the tip of the Antarctic Peninsula in late Eocene to late Oligocene time (King and Barker, 1988; Lawver et al., 1994; Coren et al., 1997; Eagles and Livermore, 2002). Opening of Jane Basin (up to 3,300 m deep) probably began slightly later (Lawver et al., 1991, 1994), and may have continued until the middle Miocene according to Maldonado et al. (1998).

From SCS data on the SOM, King and Barker (1988) defined pre-rift, syn-rift, and post-rift units. The post-rift sediments are less than 1 km thick (e.g. Busetti et al., 2001, 2002) and were drilled at ODP Site 695 (1,300 m water depth) and ODP Site 696 (600 m water depth) (Fig. AP-3). They comprise Oligocene or early Miocene to Quaternary terrigenous sediments, with rare coarse-grained IRD until the late Miocene ($\sim$8.7 Ma) and common IRD thereafter. Middle Miocene to Quaternary sediments are hemipelagic and diatomaceous muds and oozes (Barker et al., 1988a, b). ODP Site 696 also sampled syn-rift Eocene sandy mudstones (Sequence 2) that have nannofossil assemblages and clay minerals suggesting a relatively warm climate, and palynoflora indicating temperate beech forests and ferns on West Antarctica. Drilling results suggest intermittent glaciation with little sea ice during most of the Miocene and a persistent ice cap to sea-level on West Antarctica since the late Miocene. Herron and Anderson (1990) place the maximum late Quaternary grounding line advance at the 300 m isobath, and consider open-marine conditions to have existed over the SOM since 6,000 y. B.P. based on SCS and seafloor core data.

In Powell Basin, post-early-rift sediments are up to 3 km thick. King et al. (1997) identified two seismic units with low reflectivity below and high

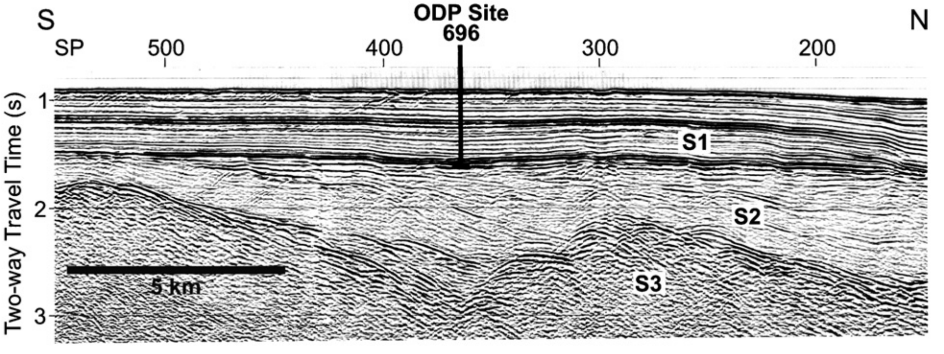

Figure AP-3: Part of seismic line AMG845-18, showing the setting of ODP Site 696 in relation to the seismic units (S1–S3) described by King and Barker (1988). Vertical exaggeration at the seafloor is 3.3:1. Adapted from Barker et al., 1988a. ODP Site 696 location shown in Fig. AP-1.

reflectivity above. They interpret the change as recording the onset of glacial–interglacial cyclicity in the supply of coarse detritus to the basin in the late Miocene. A similar upward change in reflectivity is observed in Jane Basin (Maldonado et al., 1998). The reflectivity change may also be due to silica diagenesis (e.g. Lonsdale, 1990; Volpi et al., 2003). Maldonado et al. (2006) identify five seismic units in Jane and neighbouring ocean basins, and relate changes in seismic characteristics to variations in bottom water flow since the middle Miocene. ODP Site 697 was drilled in Jane Basin (Fig. AP-1) to ~323 mbsf, and recovered mainly early Pliocene and younger hemipelagic sediments with IRD throughout; however, IRD is abundant only near the base of the sequence (Barker et al., 1988a, b). Other seismic studies of Powell Basin (e.g. Kavoun and Vinnikovskaya, 1994; Coren et al., 1997; Viseras and Maldonado, 1999) focus on the post-early Oligocene rift history of the basin, but are limited in paleoclimate interpretations by the lack of drilling data.

5.6.3. The South Shetland Islands Region

This subregion includes the Bransfield Strait and the continental margin around the South Shetland Islands (Fig. AP-1). Bransfield Strait is a 2,000 m deep rift basin that is actively extending at 7 mm/y. (Dietrich et al., 2004). The time of initial extension and the oldest age of basin sediments are uncertain, but may be 4 Ma (Barker and Dalziel, 1983) or ~6 Ma (Larter and Barker, 1991a). Gambôa and Maldonado (1990) speculate that

Bransfield Strait may have opened earlier, during the early Miocene, and have been continuous with mid-shelf basins to the southwest.

From MCS data, Gambôa and Maldonado (1990) identify 'rift' and 'drift' sequences in Bransfield Strait. 'Drift' sequences prograde the shelf and are about 1 km thick. In SCS data, Jeffers and Anderson (1990) define four glacio-eustatic sequences within the 'drift' sequences, and interpret all four sequences as being younger than 3 Ma. Prieto et al. (1999) use different SCS data to define eight seismic units that comprise interfingering slope and basinal deposits within the 'drift' sequences. They interpret the slope units as having been deposited directly from grounded ice during glacial periods, and interpret the basinal units as having been deposited by mass flow processes during deglaciations and interglacial periods.

From SCS data, Banfield and Anderson (1995) identify sediment mound features that they infer to be glacial grounding moraines in up to 1,000 m water depth on the southeastern flank of Bransfield Strait. They speculate that mounds at ~700 m depth mark the maximum advance during the LGM. Deep troughs with mega-scale lineations are incised into the shelf and are interpreted as the paths of palaeo-ice streams (Banfield and Anderson, 1995; Canals et al., 2002).

MCS profiles across the continental slope NW of the South Shetland Islands reveal a forearc basin, with more than 1.5 km sediments, that is bounded to the NW by a small accretionary prism (Maldonado et al., 1994a, b). The prism overthrusts trench-fill sediments that may have been deposited rapidly and are up to 1 km thick (Maldonado et al., 1994a, b; Kim et al., 1995).

Other seismic-reflection surveys have been done in the region by British, Polish, German, Spanish, US, Italian, Chinese and Korean research groups, but published results focus on the tectonic evolution of the region and tectonic processes (Barker, 1976; Guterch et al., 1985; GRAPE Team, 1990; Acosta et al., 1992; Henriet et al., 1992; Grad et al., 1993; Barker and Austin, 1994, 1998; Bochu et al., 1995; Gràcia et al., 1996; Jin et al., 1996; Jin and Kim, 1998; Prieto et al., 1998; Jin et al., 2002), on gas hydrates (Lodolo et al., 1993, 2002; Tinivella et al., 1998, 2002; Jin et al., 2003), and on a large submarine slide (Imbo et al., 2003).

Swath bathymetry data exist over most deep-water parts (>1,000 m) of Bransfield Strait (Lawver et al., 1996; Gràcia et al., 1997). Along Boyd Strait, 'bundle structures' and mega-scale glacial lineations occur and confirm palaeo-ice stream flow during glacial periods (Canals et al., 2000; COHIMAR/SEDANO Scientific Party, 2003). MCS data along outer Boyd Strait reveal glacial progradation of the margin (Maldonado et al., 1994a, b), and deep-tow boomer profiles reveal a glacier grounding zone wedge near the shelf edge (Vanneste and Larter, 1995).

The only scientific drilling in the South Shetland Islands region was done at SHALDRIL-I Site 1 in Maxwell Bay (Fig. AP-1), where an expanded sequence of Holocene diatomaceous muds, ~105 m thick, overlying a clay-rich diamicton was sampled (Shipboard Scientific Party, 2005).

5.6.4. The Pacific Margin

The Pacific margin includes the region southwest from the South Shetland Islands to 70°S and 80°W. This is a former active margin where ridge-crest segments were progressively subducted (Larter and Barker, 1991a; Henriet et al., 1992), followed by 1–4 m.y. of uplift and then long-term subsidence (Larter and Barker, 1989, 1991b; Anderson et al., 1990; Gambôa and Maldonado, 1990; Bart and Anderson, 1995, 1996, 2000; Larter et al., 1997). Seismic profiles show that outer shelf sequences are separated from NW-SE trending mid-shelf basins by the Mid-shelf High (MSH) (Kimura, 1982; Anderson et al., 1990; Gambôa and Maldonado, 1990; Larter et al., 1997).

Several research groups have conducted seismic studies in the area (Kimura, 1982; Larter and Barker, 1989, 1991b; Anderson et al., 1990; Gambôa and Maldonado, 1990; Henriet et al., 1992; Bart and Anderson, 1995, 1996, 2000; McGinnis and Hayes, 1995; Rebesco et al., 1996, 1997, 2002, 2006; McGinnis et al., 1997; Larter et al., 1997; Jin et al., 2002; Jabaloy et al., 2003; Hernández-Molina et al., 2006a). Cenozoic sequences have been drilled at DSDP Site 325 (Hollister et al., 1976) and at multiple sites during ODP Leg 178 (Barker et al., 1999).

Evidence of Oligocene glaciation exists on King George Island (Birkenmajer, 1991; Dingle and Lavelle, 1998; Troedson and Smellie, 2002), but offshore the first ice sheets on the Pacific margin are inferred from early Miocene IRD at DSDP Site 325 (Fig. AP-1). The oldest sediments from ODP Leg 178 are drift deposits at ODP Site 1095, dated at 9.6 Ma, where all cores show glacial influence and sedimentation rates decrease steadily from the late Miocene to the Quaternary. From seismic studies, Rebesco et al. (1996, 1997, 2002) suggest that sediment drift deposition began around the middle Miocene, with most growth in the late Miocene. However, Hernández-Molina et al. (2004, 2006b) describe a buried sediment drift of early Miocene age (Fig. AP-1). Uenzelmann-Neben (2006) also interprets depositional patterns of early Miocene continental rise sediments as reflecting bottom current influence, but infers a different flow direction. A regular supply of both glacially derived terrigenous sediments and interglacial biogenic sediments has reached the continental rise since at least the middle Miocene.

The outer continental shelf is underlain by depositional sequences that thicken seaward (Larter and Barker, 1989, 1991b; Anderson et al., 1990; Gambôa and Maldonado, 1990; Larter and Cunningham, 1993; Bart and Anderson, 1995; Table AP-1). Aggrading sequences (S3) without a distinct paleo-shelf edge (PSE) are unconformably overlain by prograding sequences (S2, S1) with an abrupt PSE (Foldout AP-1). The change occurs at the S3/S2 boundary of Larter and Barker (1989, 1991b) and is observed all along the Pacific margin (Anderson et al., 1990; Bart and Anderson, 1995, Larter et al., 1997; Jin et al., 2002) and west along the margin of the Bellingshausen and Amundsen Seas (Nitsche et al., 1997). Drilling at ODP Sites 1097 and 1103, although with very poor recovery, suggests that the change occurred between 8 and 6 Ma (Iwai and Winter, 2002; Bart et al., 2005). Cores from S3 are diamictons with interbedded mudstones and graded sandstones, interpreted by Eyles et al. (2001) as continental slope deposits, although seismic profiles suggest a palaeo-shelf to slope transition further offshore. Cores from S1 and the upper part of S2 show abundant evidence for having been deposited subglacially (Eyles et al., 2001).

Larter and Barker (1989, 1991b) and Larter et al. (1997) interpreted the S3/S2 boundary as representing the onset of frequent advances of grounded ice to the palaeo-shelf edge. However, Bart and Anderson (1995) and Bart et al. (2005, 2007) suggest that palaeo-ice streams cut erosional troughs within S3 and hence existed earlier than the S3/S2 boundary. Although equivocal, the boundary could represent a change in the typical extent of glacial advances, in the dynamic behaviour of ice sheets that advanced onto the shelf, or in the way the ice transported sediments (Larter et al., 1997; Hernández-Molina et al., 2006a).

Going up-section above the S3/S2 boundary, foreset stratal dips generally increase and PSE progradation in individual sequences decreases (Foldout AP-1). The regional S2/S1 boundary within the upper sedimentary section may have been produced by ice-sheet erosion during glacial periods and lower sea levels after the Late Pliocene increase in the volume of Northern Hemisphere ice sheets (Larter and Barker, 1989, 1991b). By seismic correlation across >100 km to ODP Site 1101, Rebesco et al. (2006) estimate an age of ~ 3 Ma for a boundary that they identify as S2/S1. However, this boundary marks a change in stratal geometry that is generally characteristic of S3/S2, and Larter (2007) suggests that it probably corresponds to this earlier unconformity.

Table AP-1: Summary of stratigraphic schemes used in previous publications to describe the late Miocene to recent depositional sequences on the Pacific margin of the Antarctic Peninsula.

Continental rise		Outer continental shelf off Adelaide Island				Outer continental shelf off Anvers Island		
Rebesco et al. (1997, 2002)	Sites 1095 and 1101	Hernández-Molina et al. (2006a)	Larter et al. (1997)	Site 1097	Bart and Anderson (1995)	Bart and Anderson (1995)	Site 1103	Larter and Barker (1989, 1991b)
		SU1						
M1			S1					S1
		SU2						
—	2.9 Ma	—	—	0.35–4.25 Ma	2.9	2.9	~ 2.5 Ma	—
M2		SU3						S2
—	5.3 Ma	—	S2					
		SU4						
M3		—	—	6.1–7.9 Ma	3.13	3.9	< 7.4 Ma	—
—	9.6 Ma		S3					S3
M4								

Age constraints on sequence boundaries obtained from ODP Leg 178 drill sites are also shown. N.B. Larter et al. (1997) originally described the sequences offshore from Adelaide Island as A1–A3 because of uncertainty in correlations along the shelf, but as results from Leg 178 suggest that the boundaries are of similar age to the S1–S3 sequences described previously offshore from Anvers Island, the same sequence names are shown here for both areas.

Mid-shelf basins contain up to 2 km of sediment in a broad synform that is truncated at shallow depth beneath the seafloor (Kimura, 1982; Anderson et al., 1990; Gambôa and Maldonado, 1990; Larter et al., 1997), making the succession accessible to shallow drilling. However, these sediments have not been sampled, except for the thin Quaternary cover. Basin sediments are probably all Tertiary and may be as young as early Miocene off Adelaide Island, and middle Miocene off Anvers Island (Larter et al., 1997). The inner shelf is mostly shallower than 200 m, but has deep troughs, such as the Palmer Deep where ODP Sites 1098 and 1099 were drilled in 1,400 m of water. Holocene successions ~47 and ~108 m thick were recovered at ODP Sites 1098 and 1099, respectively (Shipboard Scientific Party, 1999; Domack et al., 2001; Ishman and Sperling, 2002; Leventer et al., 2002; Shevenell and Kennett, 2002).

Swath bathymetric data show seafloor features of subglacial origin on the shelf (Ó Cofaigh et al., 2002; Dowdeswell et al., 2004; Amblas et al., 2006), and confirm that a grounded ice sheet with ice streams extended to the shelf edge during the LGM (Pudsey et al., 1994; Larter and Vanneste, 1995). Seafloor core data indicate that retreat of the ice sheet from the outer and middle shelf after the LGM occurred between 18,500 and 13,000 cal. y. B.P. (Pudsey et al., 1994; Heroy and Anderson, 2005).

5.7. Other Sectors of the Antarctic Continental Margin

Other sectors of the Antarctic margin, than the five ANTOSTRAT project working areas discussed above, have been studied more fully than previously during the past 5–7 years, in a time of renewed interest in MCS studies of the continental margin. These regions include similar geomorphic and stratigraphic features. Although we do not include them in the discussion below due to space considerations, we include here representative citations to some of the studies published for the Bellingshausen and Amundsen seas (Hollister et al., 1976; Tucholke and Houtz, 1976; Tucholke, 1977; Kimura, 1982; Yamaguchi et al., 1988; Cunningham et al., 1994, 2002; Gohl et al., 1997, 2007; Nitsche et al., 1997, 2000; Wellner et al., 2001, 2006; Lowe and Anderson, 2002; Ó Cofaigh et al., 2005; Dowdeswell et al., 2006; Evans et al., 2006; Scheuer et al., 2006a, b; Larter et al., 2007; Uenzelmann-Neben et al., 2007) and for offshore areas of Queen Maud Land and Enderby Land (Kuvaas et al., 2004a, b, 2005; Hinz et al., 2005; Stagg et al., 2004a, b; Leitchenkov et al., 2007; Solli et al., 2007a, b, c).

5.8. Discussion

Our discussion focuses on integrating key observations and inferences from the Antarctic continental margin to summarize a Cenozoic glacial history from the stratigraphic record. We recognize the limitations of the seismic and drilling data sets used. Seismic data image regional and up-section changes, but only provide a relative history of inferred events and processes. Drilling data provide a defined stratigraphic history, but one that is valid only at the local drilling site. There is an extensive published literature that illustrates the large spatial and temporal variability of features and processes at various scales, depending on the resolution and extent of data analysed. We selectively discuss the widespread seismic stratigraphic variations and the long- and short-period geologic transitions in cores, all of which point to a varied history of non-glacial and glacial events on the continental margin. The discussion is necessarily condensed due to the great breadth of the topics and the limited space herein.

We abbreviate offshore geographic regions as: Ross Sea (RS), Antarctic Peninsula (AP), Weddell Sea (WS), Prydz Bay (PB) and Wilkes Land (WL), and prefix these abbreviations with east (E) and west (W), such as western Ross Sea (WRS) (Fig. I-1).

5.8.1. Regional Seismic Stratigraphic Variations: Similarities and Differences

Stratigraphers have long recognized sedimentary sequences and bounding regional unconformities in seismic-reflection data across the Antarctic continental margin (e.g. Hinz and Block, 1984; Wannesson et al., 1985; Hinz and Kristoffersen, 1987; Cooper et al., 1995). These sequences, principally of inferred Cenozoic age, commonly have similar seismic geometries around Antarctica (e.g. Cooper et al., 1991b; Anderson, 1999). Some geometries are unique to polar continental margins, whereas other geometries are like those of low-latitude non-polar margins (e.g. Hinz and Block, 1984; Bartek and Anderson, 1991; Table D-1). A unified circum-Antarctic seismic stratigraphy does not exist, but an International effort to compile one via the CASP project is in progress (Davey and Cooper, 2007). Numerous separate and sometimes different seismic stratigraphies exist for various localities.

Many seismic features have been cited to suggest intermittent ice on the Antarctic margin (Table D-1), but those giving the strongest evidence for ice are the regional seismic unconformities, the broad erosional troughs and depositional banks on the continental shelf, and the large-scale fans and

Table D1-1: Common large-scale geomorphic and seismic stratigraphic features of the Antarctic continental margin (listed by location and decreasing inferred age).

Feature	Regions	Process[a]	Timing[b]
Continental shelf			
A. Deep regional seismic unconformities on the shelf (lower ~1/3 of sedimentary section)	PB, RS	Eustacy	Cretaceous to late Oligocene (?)
B. Shallow regional seismic unconformities on the shelf (upper ~2/3 of section)	All	Ice-sheet erosion	late Oligocene (?) and younger
C. Prograded and aggraded sequences under the outer shelf	All	Sediment carried to the shelf by glaciers	Oligocene and younger
D. Mound features with chaotic seismic facies	All	Ice-sheet deposition	late Oligocene and younger
E. Broad cross shelf troughs and adjacent banks	All	Ice-stream erosion	early Miocene and younger
F. Overdeepened and foredeepened continental shelf	All	Ice-sheet erosion	mid-Miocene and younger
Continental slope			
G. Regional seismic unconformities	All	Bottom currents	Cretaceous and younger
H. Massive sediment fan on the slope at the outlet of a broad cross-shelf trough	PB, WS	Sediment deposited at shelf edge by one broad ice stream	early Oligocene and younger (WS); early Pliocene and younger (PB)
I. Steep slopes and migrating high-relief channels	All	Bottom currents with coarse sediment	Oligocene and younger
J. Variable size sediment fans on the upper slope at mouths of seafloor and buried troughs.	WL, RS, AP	Sediment deposited at shelf edge by multiple ice streams	late Miocene and younger
Continental rise			
K. Regional seismic unconformities	All	Bottom currents and diagenesis	Cretaceous and younger

Table D1-1: (*Continued*).

Feature	Regions	Process[a]	Timing[b]
L. Large sediment drift features	All	Bottom currents and downslope sediment supply	early Miocene and younger
M. An up-section landward shift of depocenters from rise to slope.	All	Reduction of sediment supply to rise	mid-Miocene and younger

[a]The principal process is listed – others such as lithospheric loading, sediment loading, paleoceanographic processes, diagenesis, etc. are also commonly involved.
[b]Initiation time of features varies in different regions.

prograding deposits on the continental slope at the mouths of the shelf troughs. These features are observed on all sediment-covered segments of the Antarctic margin, in East and West Antarctica, and principally occur in the upper part of the stratigraphic section. These features are increasingly common up-section, indicating more abundant glacial events more recently. The ubiquitous overdeepened and foredeepened depth profile of the continental shelf is the ultimate evidence of sustained strong glacial erosion of the entire Antarctic margin.

Ten Brink et al. (1995) modelled the geometries of the seafloor and stratigraphic sections on the continental shelf and upper slope, incorporating lithospheric, glacial and eustatic processes in the models. They showed that multiple advances and retreats of grounded ice sheets across the continental shelf, coupled with redistribution of sediment from onshore and shelf areas to the continental slope, are required to match the observed geometries. Eustatic and paleoceanographic processes are important for sediment redistribution, especially on the continental slope and rise, but are not sufficient by themselves to explain the shelf erosion and prograding geometries beneath the outer continental shelf. Bartek et al. (1991) illustrated that the stratal signatures of the Oligocene and younger sections in the eastern Ross Sea (i.e. unconformities and prograding sections) are similar to those of low-latitude non-polar margins, indicating that the Neogene stratal signature results from glacio-eustatic fluctuations.

Seismic data provide a relative history of increasing circum-Antarctic glacial events, as noted above, but drilling and seafloor coring provide the only absolute age control and ground truth of glacial lithologies and processes. Definitive ages are limited due to the small number of cored sites, which in turn are biased toward sampling of shallow younger sections.

The lithostratigraphic record from proximal drilling and dredging on the Antarctic margin 'establishes' a general history (at the drill sites) of no regional glaciers in Cretaceous and earlier times on the shelf (PB, RS, WL) and on the slope (WS). Evidence of glacial episodes is first seen in the late Eocene to early Oligocene as diamicts from grounded ice on the shelf (PB, RS) and from glacial erratics on the slope (WS). Upper Oligocene glacial marine deposits are sampled on the shelf (RS) and slope (WS). Lower Miocene sections show increasing evidence of ice and deep-ocean currents, with IRD and sediment drifts on the rise (PB, WL, AP, WS?) and glacial marine sediments and diamicts on the shelf (RS). The middle Miocene has an increased glacial hemipelagic signature on the rise (PB), and glacial marine deposits on the shelf (RS). The late Miocene and early Pliocene were times of enhanced glacial activity, as recorded by: (1) shelf deposits of glacial diamicts (PB, AP) and glacial marine sediments (RS, AP); (2) glacial marine sediments on the slope (WS, WL); and (3) rise deposits of glacial hemipelagics (PB, WL, RS, AP) and turbidites (WL, WS, AP). Upper Neogene deposits are principally glacial on the shelf (PB, RS, AP), slope (PB, WS) and rise (PB, WL, RS, AP, WS). Based on recovered drill cores and Antarctic Peninsula coastal geology, the general history of events for East and West Antarctica is essentially the same since the early Oligocene. However, the middle Miocene and Oligocene history for offshore West Antarctica is based on only two Ross Sea DSDP cores (Hayes and Frakes, 1975) and two tentatively dated SHALDRIL cores from the western Weddell Sea (Anderson et al., 2006; Shipboard Scientific Party, 2006).

The above general history at the sparse drill sites has been greatly expanded by many investigators who have traced seismic unconformities and seismic stratigraphic units from core sites and rare onshore sedimentary sections up to hundreds of km to infer ages and lithofacies for key stratigraphic features listed in Table D-1. The expanded seismic stratigraphic history includes inferences of the following (although uncertainties about these inferences are inherently greater than the uncertainties about ages at drillsites):

- *A pre-ice-sheet to early-glacial period (Cretaceous to early Oligocene):* On the inner and mid shelf, variable seismic facies (WRS, PB), narrow channel geometries (PB) and sea-floor dredged/cored rocks indicate the presence of pre-ice-sheet subaerial, fluvial and shallow marine environments in the Cretaceous. These are unconformably overlain (WRS, PB) by upper Eocene to lower Oligocene early glacial sediments. This transition, from pre-ice-sheet to early glacial conditions, has not been sampled elsewhere on the shelf. Beneath the slope and upper rise, thick sediment sections are observed (all areas), but are not yet well imaged and mapped in most areas.

• *Aggrading shelf period (Oligocene):* On the shelf, stratal geometries in drilled Oligocene glaciomarine sections mostly aggrade the PSEs in PB and ERS, but PSEs appear to prograde where the shelf is strongly uplifted and eroded (WWS). Aggrading PSE geometries occur in unsampled areas of the outer shelf (WL, AP). On the slope, geometries show high-relief paleo-slope-canyons (PB, WL, RS, WS), and in the WS, deposition of the massive Crary Fan (WS) began. On the rise, seismic facies indicate higher energy depositional environments with paleo-channel-levee systems first developing (PB, WL, RS, AP, WS). Where drilled (PB, WL, RS), lithologies from this period have glacial components indicating onshore glaciers. Backstripping calculations indicate normal shelf water-depths (PB, RS).

• *Uniform prograding shelf (early and middle Miocene):* In many regions, seismic sequences uniformly prograde the continental shelf edge, with an up-section increase in the dips of foreset-beds (glaciomarine deposits) and variable erosion of topset strata (with diamicton) (PB, WL, RS, AP, WS). Sea-level stratigraphic control began to shift to ice-dominated stratigraphic control, with documented cyclic shelf erosion by grounded ice sheets. Initial regional erosion and overdeepening of East Antarctic shelves commenced (PB, RS, WL). Slope geometries indicate canyon shifting and infilling (PB, WL, RS) and fan growth (WS), with rise geometries showing the construction of large drift mounds (WWS, PB, WL, AP) and channel-levees (WL, WS, AP, PB). Abundant contourite deposits (PB, AP) with some turbidites (AP, WL) are documented. Glacial and interglacial sediment volumes decreased on the rise (PB, AP), but increased on the slope (WS).

• *Local and focused prograding shelf (late Miocene to Pleistocene):* A prominent regional unconformity occurs in the late Miocene to early Pliocene across all margin segments (PB (A, PP12); WL (U8); RS (U2); AP (BGMS) WS (W5)). The unconformity marks a circum-Antarctic change from areas of uniform PSE progradation to local-arcuate and broadly focused PSE progradation into small and/or overlapping upper-slope fans (e.g. QML, WL, AP) and broad trough-mouth fans (e.g. PB, WS) lying at or near the end of cross-shelf troughs. Strong regional shelf erosion, by both narrow and wide ice streams early in this period, was followed by regional deposition of topset banks composed principally of glacial diamicton (PB, AP, WL, WS?) and glacial marine (RS) sediment. Periods of pelagic sedimentation on the shelf indicate open water and sea ice. On the slope, foreset dips steepened as fans formed above the unconformity. On the rise, sedimentation rates decreased (PB, AP) and depocentres shifted progressively landward, moving from the rise to beneath the slope (PB, WL, AP, WS, AP?). Stratigraphic control was dominated by episodic grounded ice, with sediment deposition by ice and sediment distribution by ocean-currents.

- *Sediment drape (late Pleistocene and Holocene):* Thin well-layered acoustic units commonly infill shelf depressions and drape across the slope and rise (All regions). These units provide a record of pelagic sedimentation from the last few interglacial and glacial periods. Deep inner-shelf basins, in particular, trap Holocene biogenic sediments with that were deposited at very high sedimentation rates; these biogenic sediments yield an ultra-high- to high-resolution (i.e. decadal to millennial) record of climate variability (AP, WL, PB).

5.8.2. Long- and Short-Period Transitions in the Geologic Record

The seismic stratigraphic record provides a regional framework that illustrates distinct changes in the morphology of the Antarctic margin over the last 60 m.y. Drill cores provide the direct 'ground truth' geologic record of both long-period (m.y.) and short-period (k.y.) transitions (Table D-2). Some of the transitions in drill cores are reflected in the seismic stratigraphic framework and others are not. All transitions, however, are important in deciphering Antarctic paleoenvironments. In this discussion, we focus on lithostratigraphic changes in drill cores, and leave the discussion of isotopic, biostratigraphic and other relevant variations to authors of other chapters of this book. Our intent is to use the proximal lithostratigraphic drilling record from the continental margin to independently evaluate paleoenvironmental history, where possible.

Drill cores from two segments of the continental shelf provide a general lithostratigraphic framework for the long-period systematic transition from non-glacial (Mesozoic) to fluctuating glacial and interglacial (late Cenozoic) paleo-depositional environments. At the mid-shelf of Prydz Bay, cores document the changes from subaerial non-glacial (Cretaceous) to fluvial/lagoonal early glacial (late Eocene) to shallow marine early glacial (early Oligocene) to subglacial deep shelf (early Pliocene) to interglacial open-marine (Holocene) conditions. A similar transition is documented in the Ross Sea (McMurdo Sound), from subaerial non-glacial (Mesozoic) to shallow marine early glacial (early Oligocene) to fluctuating subglacial and marine glacial (early Miocene to Holocene) to interglacial open-marine (Holocene) environments. Large hiatuses exist in the shelf cores.

Improved resolution of the continuity and timing of changes is seen in drill cores from the continental rise, where geologic continuity and core recovery

Table D2-2: Lithostratigraphic transitions in the geologic records from drill cores from the antarctic margin (listed by duration and decreasing inferred age).

Feature	Regions	Process[a]	Timing
Long-period changes (m.y.)			
On the shelf: up-section lithologic changes from alluvial to fluvial to shallow marine to marine glacial to subglacial	PB	Subsiding graben/ shelf with increasing ice to the shelf	Cretaceous to Pliocene
On the rise, sedimentation rates of hemipelagic sediments decrease smoothly while on the slope, sedimentation rates increase stepwise (i.e. in distinct stratigraphic units)	PB, AP, WS	Likely decrease in onshore sediment supply coincident with a shift in deposition from the rise to the slope	early Miocene to early Pliocene
On the rise, up-section increases in IRD, diatom content; shift kaolinite and glauconite	PB	Erosion of shelf basins by grounded ice sheets	middle Miocene (~17–14 m.y.)
Short-period changes (k.y.)			
On the inner shelf: cyclic changes from diamict (glacial) to glacial marine (interglacial) facies (in early Miocene at Milankovitch frequencies)	RS	Glaciers fluctuating onto and off the shelf during glacial and interglacial times	early Oligocene to middle Miocene
On the rise: cyclic changes from terrigenous (glacial) to biogenic (interglacial) facies at Milankovitch (PB) and similar variable (AP) frequency	PB, AP	Glaciers fluctuating onto and off the shelf during glacial and interglacial times	early Miocene to early Pliocene
On the slope: shift in glacial sediment clast type: sandstone to granite	PB	Likely change in ice source area: offshore to onshore?	Between 1.1 Ma and 780 k.y.

[a]The principal process is listed.

are greater than from the shelf or slope. On the rise, there is a distinct up-section change in seismic character from well layered below to channel-levy development above (all areas) that is widely inferred due to a large influx of sediment when onshore ice sheets initiated in late Eocene to early Oligocene time. Here, the pre-ice to glacial transition has not yet been sampled by drilling. Yet, higher in the stratigraphic section of the rise, drill cores show a clear long-term parabolic decrease in the sedimentation rates within sediment drift deposits from the early Miocene (PB: 10-fold decrease) and the late Miocene (AP: 6-fold decrease) to the present. The large decreases occurred when the PSEs were prograding over distances of several tens of kilometres and aggrading up to several hundred metres, although the detailed timing of the prograding and aggrading is unknown. Regardless, the distinct changes in geometries of seismic sequences beneath the outer paleoshelves in PB and AP are not seen as abrupt changes in sediment deposition rates on the rise. Drilling on the slope (WS) shows large incremental increases in sedimentation rates for this same general period (i.e. early Miocene to early Pliocene), indicating that sediment coming from the shelf may not have reached the rise. The decreases in sedimentation rates on the rise may also reflect a decrease in the amount of sediment being eroded from onshore and shelf areas.

A notable long-term transition occurs in middle Miocene sediments (17–14 Ma) from the rise (PB). Up-section increases in IRD, diatom content, and recycled organic matter, along with changes in the types of clay and the first appearance of glauconite, point to greater ice nearby and initial erosion of shelf sedimentary basins. Evidence for strong erosion on the shelf is also seen in truncated foreset strata beneath the outer PB paleo-shelf. RS shelf drill cores are marked by a long hiatus, from mid- to late-Miocene. The hiatus and truncated shelf reflectors point to an increase in shelf erosion and overdeepening in the RS, similar to the erosion recorded on the rise at PB.

Short-period fluctuations in shelf and rise drill cores provide the strongest evidence that erosion onshore and on the shelf by fluctuating grounded ice sheets was the mechanism for sediment supply and distribution by glacial processes, as inferred from seismic-reflection data. On the RS shelf, cyclic fluctuations in glacial diamict and interglacial glaciomarine lithofacies at Milankovitch frequencies are documented for lower Miocene nearshore facies at the front of the Transantarctic Mountains, and resulted from ice advancing onto and retreating off the shelf at this time (Naish et al., 2001). On the rise (PB and AP), alternating dark- and light-coloured lithofacies with varying amounts of terrigeneous (dark) and biogenic (light) components are described throughout the lower Miocene to lower Pliocene intervals from visual observation of cores, downhole logging and physical properties measurements (PB); similar compositions variations are described from upper Miocene to Pliocene intervals in the AP. The facies are inferred to be of glacial and interglacial origin, respectively, and occur at Milankovitch frequencies in PB and similar order-of-magnitude frequencies in AP. Hence, drilling on the rise in East Antarctica and in West Antarctica has provided similar geologic evidence for fluctuating ice sheets on the shelves during the period of principal shelf progradation and aggradation – from the early Miocene to the early Pliocene.

The geologic transition in the late Miocene to the early Pliocene is the initiation of broad and narrow shelf troughs and widespread banks, lobes and upper-slope fans along the Antarctic margin (all areas); this transition is difficult to see in drill cores, but has been imaged seismically. On the rise (AP, PB), sedimentation rates decrease uniformly during this period and lithologies (e.g. clays, IRD, etc.) do not show systematic long-term changes. However, seismic geometries beneath the adjacent continental shelves show abrupt changes to rapidly prograding sections (S2/S3 beneath AP; PP-12 beneath PB). Elsewhere, drilling information is insufficient to explain why large geomorphic changes on the shelf, probably due to changes in glacial regime, are not reflected in the rates or types of sediment delivered to the rise.

5.8.3. Sea-Level and Ice-Volume Changes

Lithostratigraphic data from Antarctic margin drill cores show clear evidence on the shelf (PB, RS) for linked sea-level and ice-volume changes. This is best shown in the Oligocene through early Miocene record of cyclic glacial and interglacial lithologies near the coast in Cape Roberts cores (WRS) (Barrett, 2007). Lithostratigraphic data from the slope (PB) and rise (PB, AP) show additional direct evidence for cyclic ice-volume changes. Seismic-reflection data provide indirect evidence across the entire margin for the linked sea-level and ice-volume fluctuations that have been noted by many investigators and have been modelled in the RS (Bartek et al., 1991) and presented conceptually for all margins (ten Brink et al., 1995). The Antarctic drill cores are too limited, however, to establish the timing, magnitude and extent of individual ice sheet advances onto the continental shelf, other than for the LGM.

A comparison of the Antarctic margin proximal stratigraphic record with the global record of sea-level variations (and linked ice-volume variations) from coastal onlap, backstripping, and isotopic records since the middle

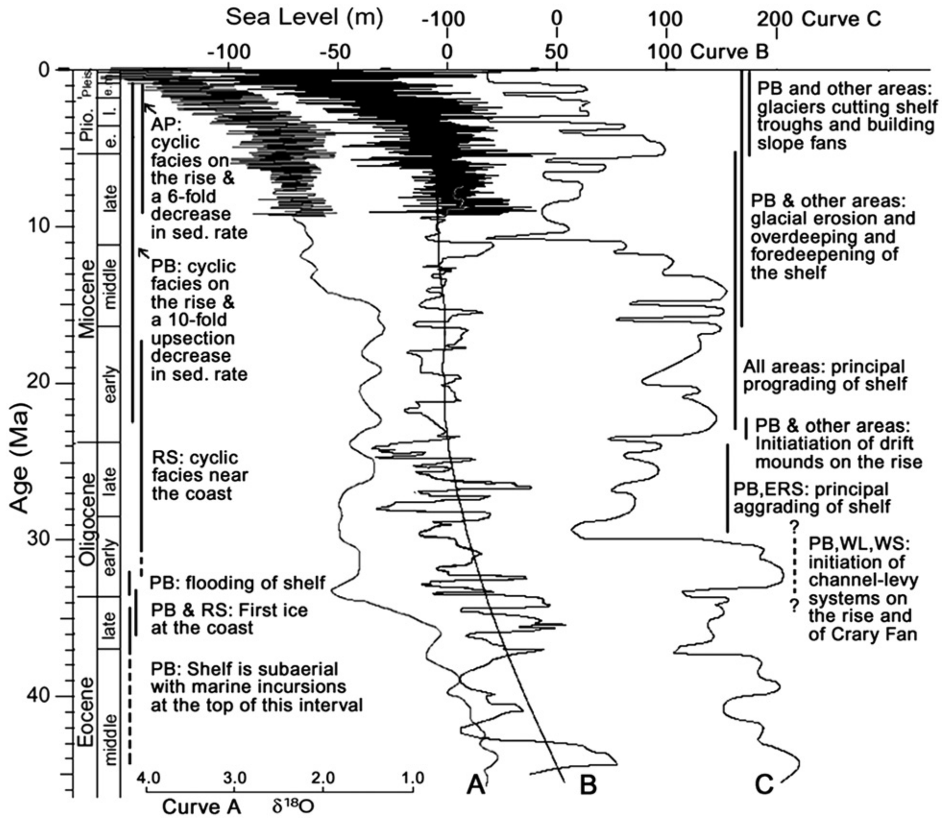

Figure D-1: Graph showing sea-level and isotope curves and principal stratigraphic events for the Antarctic continental margin. Curves are from Miller et al. (2005). Events are from text and Tables D-1 and D-2. Curve A is for benthic foraminifera. Curve B is derived from stratigraphic backstripping (>9 M.a.) and isotopic measurements (0–9 M.a.); Curve C is from Haq et al. (1987). Curves B and C have different sea-level change scales. For some periods, Antarctic stratigraphic events correlate with isotopic shifts (e.g. PB: early Oligocene unconformity and first ice sheets at the coast and mid-Miocene lithology changes and ice buildup) and with the Haq Curve (e.g. mid-to-late Miocene shelf erosion and early Pliocene and younger slope fan development with long-term sea-level lowerings).

Eocene is shown in Fig. D-1. Large differences appear between the global sea-level curves (see Miller et al. (2005) for the explanation), yet the Antarctic stratigraphic features can potentially be linked to parts of all of the curves principally because of the current uncertainty in ages of Antarctic features, especially for the Paleogene. The closest links of Antarctic features with the global curves are:

- Late Eocene and early Oligocene lowering of sea-level (first glaciers into PB and RS), followed by sea-level rise in the early Oligocene (flooding of PB).
- A long period from the Oligocene into the late Miocene of cyclic sea-level, seen in cyclic coastal deposits (WRS) and as glacial/interglacial rise-drift deposits (PB, AP)
- Abrupt sea-level lowering in the middle Miocene, seen in lithologies of rise-drift deposits (PB), followed by further sea-level lowering (with ice buildup) and enhanced erosional deepening and prograding of continental shelves by glaciers (as seen in seismic profiles from all areas).
- The systematic decrease in sea-level (and increase in ice) from the mid-Miocene to the present that corresponds with the decrease in sedimentation rates on the rise and increase in sedimentation rates on the slope. This is most pronounced since early Pliocene time, when an extensive system of shelf erosional troughs and upper-slope fans developed.

Greater resolution of the link between ice-volume variations and sea-level changes requires further drilling on the Antarctic margin.

5.9. Summary

The Antarctic continental margin holds a thick Cenozoic sedimentary section that is characterized by both long-period and short-period lithostratigraphic transitions, which are seen locally in drill cores and regionally in seismic-reflection data. Age resolution is inadequate to link individual stratigraphic events, but is sufficient to make general statements about glacial history. The transitions point to the last 40 m.y. being a period of increasing glaciation and sediment distribution by glacial processes via short-period fluctuations (e.g. Milankovitch frequencies) of grounded ice sheets across the continental shelf and accompanying sea-level changes. The proximal history is generally similar to that of distal proxy records from isotopic studies in adjacent ocean basins (e.g. Zachos et al., 2001) and from stratigraphic studies on low-latitude continental margins (e.g. Miller et al., 2005, 2000). Key inferences from the Antarctic margin for the Cenozoic, based on published data and inferences from extensive seismic-reflection and limited drilling records, are:

- Although tectonic histories differ around the Antarctic margin, similar geomorphic features (e.g. overdeepened and foredeepened seafloor; broad erosional troughs, sediment fans and drift mounds) are seen everywhere on the margin, as a result of ubiquitous fluctuating glaciers eroding and distributing sediments.

- East and West Antarctic margin segments may have similar glacial histories, based on similar geomorphologies and known ages offshore for glacial strata. Current differences result partly from lack of sufficient drilling into likely Paleogene offshore sections beneath the margin.
- Seismic geometries and facies from all segments of the continental margin show evidence for up-section increases in the dynamic movement of sediment across the margin (e.g. shelf troughs, slope sediment fans, channel-levee systems) and along the margin (e.g. rise-drift deposits), reflecting increased glacial and ocean current activity from the Oligocene to the present.
- Stratal geometries of the continental shelf and slope were controlled principally by eustatic changes (with ice fluctuations) from the Paleogene to about the middle Miocene, and thereafter principally by fluctuating grounded glaciers (in tandem with sea-level changes) on the shelf, leading to the overdeepening and foredeepening of the shelf.
- Extensive prograding and aggrading of the continental shelf from the early Miocene to the latest Neogene is the principal result of sediment dispersal by ice sheets during glacial and interglacial periods at near-Milankovitch periodicities, as documented from drilling of drift deposits on the continental rise in East Antarctica (PB) and West Antarctica (AP), and from near-coastal sequences (RS).
- The principal locus of sediment deposition on the margin has shifted from the outer rise (and beyond) during the Paleogene, to the inner rise and slope in the early Miocene to early Pliocene, and to the mid slope thereafter. The depocentre shift reflects the increases in glacial activity (and increases in ocean currents) and decrease in sediment being supplied due to erosion of onshore and shelf areas.
- Specific circum-Antarctic glacial events in the evolution of the margin include: first glaciers at the coast and initiation of channel-levee systems on the rise and the Crary Fan (early Oligocene); fluctuating glaciers, initial rapid progradation of the continental shelf, and initial growth of drift mounds and large levees on the rise (early Miocene); onshore ice buildup and initial overdeepening of the continental shelves (middle Miocene); dynamic ice movements and initial widespread development of cross-shelf troughs and upper-slope fans (early Pliocene); widespread deposition of biogenic interglacial sediment in deep inner-shelf troughs (Holocene).

Additional advances in our understanding of Antarctica's glacial history and the varied effects of ice sheets on the paleoceanographic and lithostratigraphic processes of the Antarctic continental margin can only be achieved through additional offshore deep stratigraphic drilling studies, such as the current IODP, ANDRILL and SHALDRIL projects.

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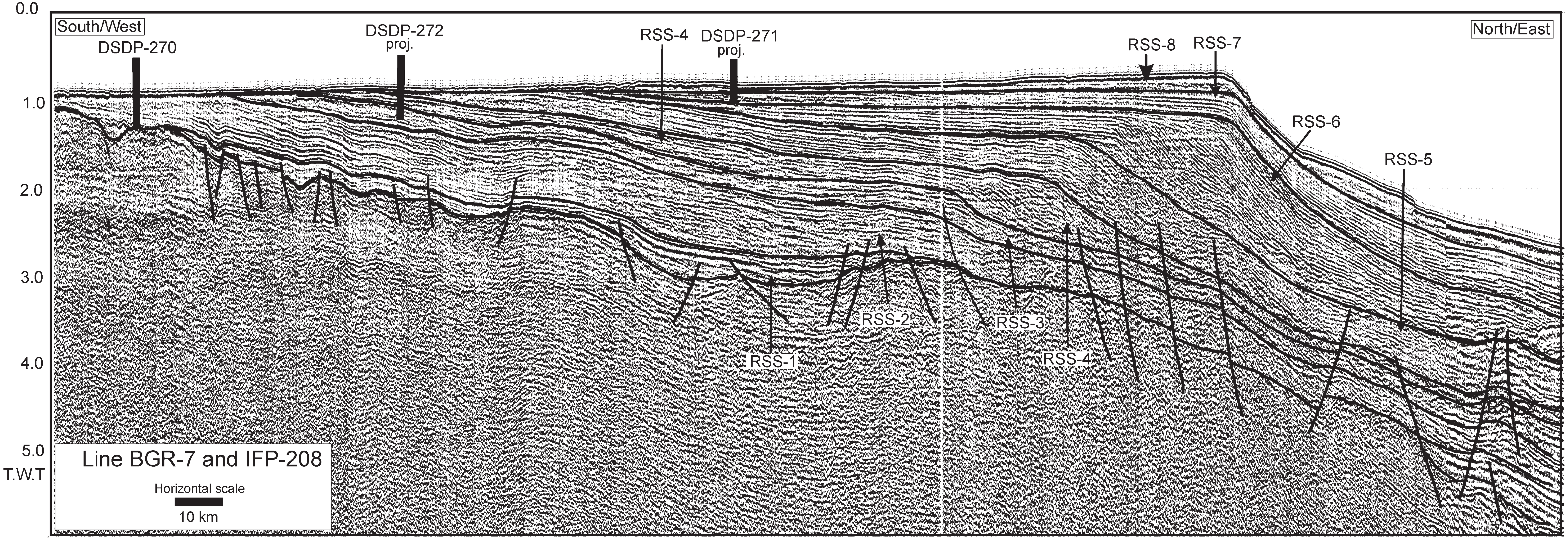
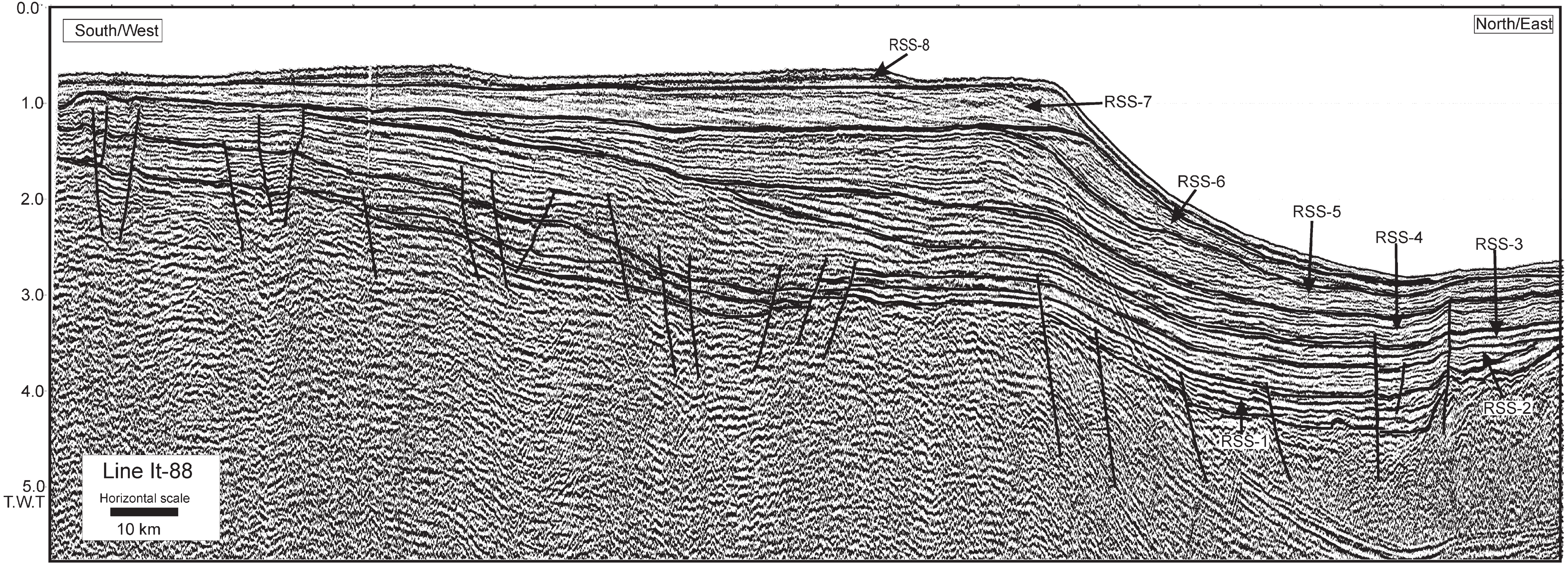
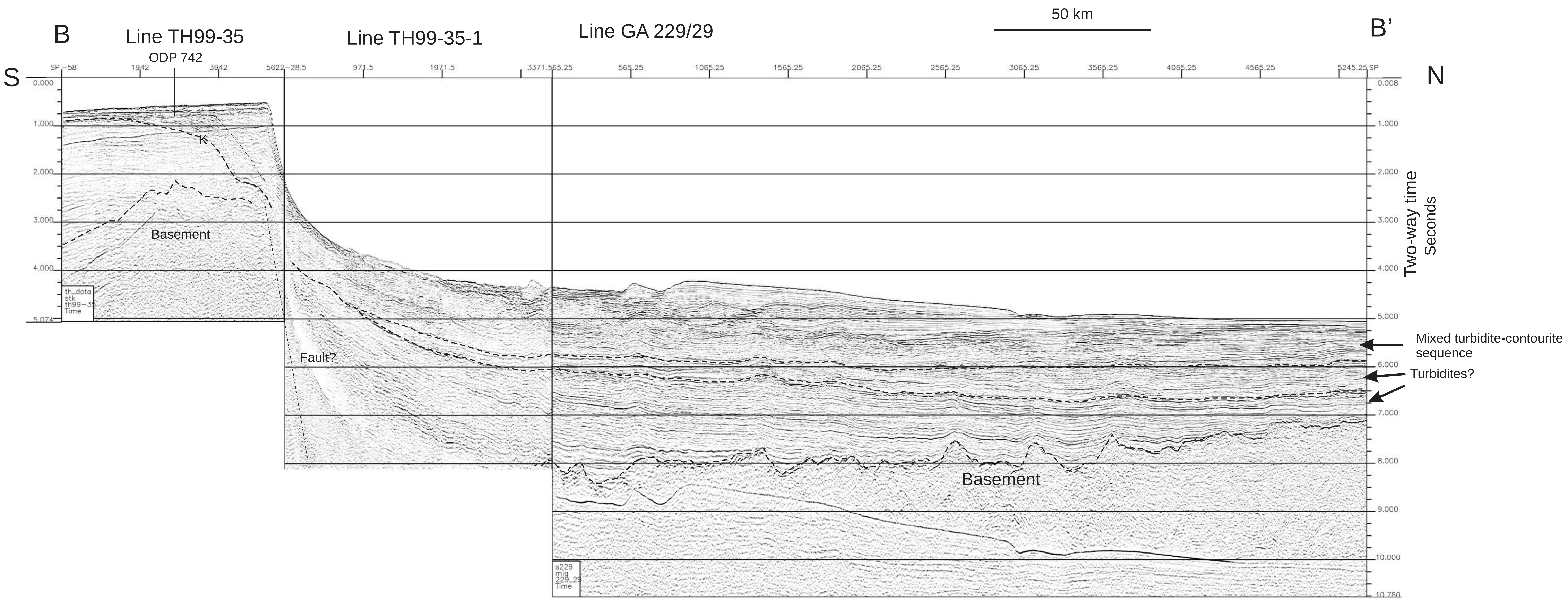


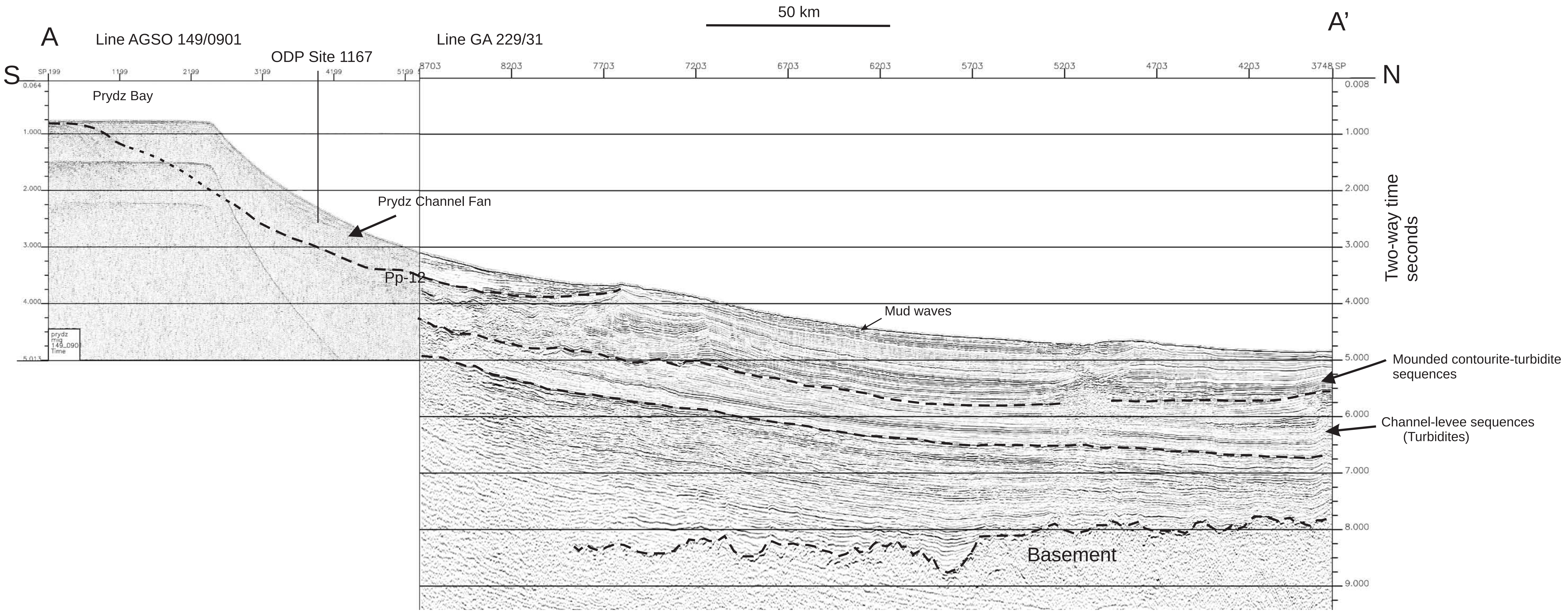
Foldout RS-1: 'Type section' from the Eastern basin (modified from Cooper et al., 1995). The section is a compilation of seismic lines BGR-7 and IFP-208. RSS-1 are inferred pre-ice deposits, RSS-2 and -3 are early-glacial glaciomarine deposits, RSS-4, -5 and -6 are glaciomarine deposits of the ice-sheet growth phase, and RSS-7 and -8 are glaciomarine deposits of the polar ice-sheet phase. See Fig. RS-1 for location.



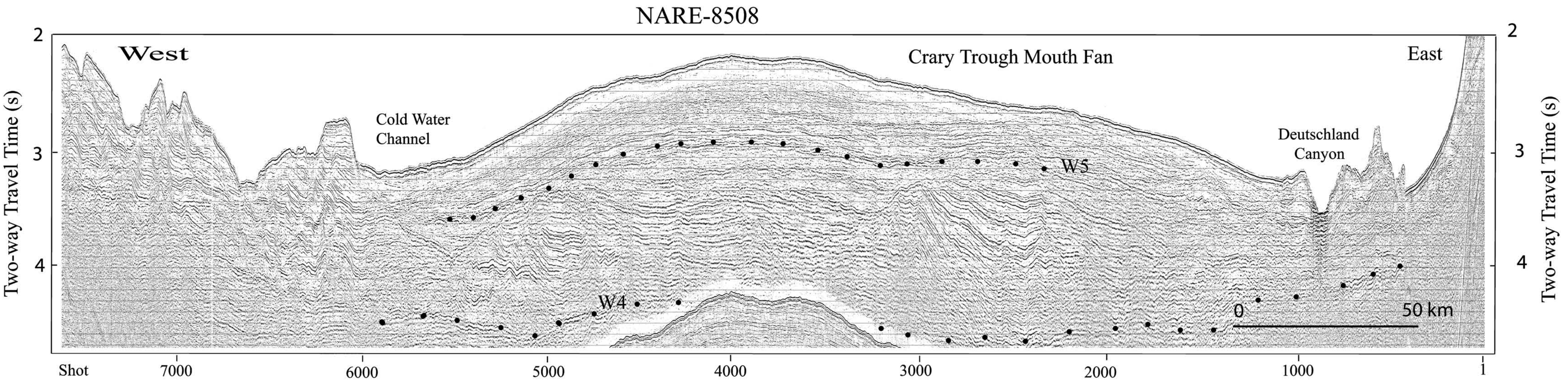
Foldout RS-2: 'Type section' from the Northern basin (modified from Cooper et al., 1995). The stratigraphy and origin of sediments are similar to those for the 'type section' in the Eastern basin (Foldout RS-1). RSS-1 is a basin-fill sequence, RSS-2 and -3 mostly aggrade, RSS-4, -5 and -6 mostly prograde and have with eroded topset beds, RSS-7 and -8 have aggrading geometries. See Fig. RS-1 for location.



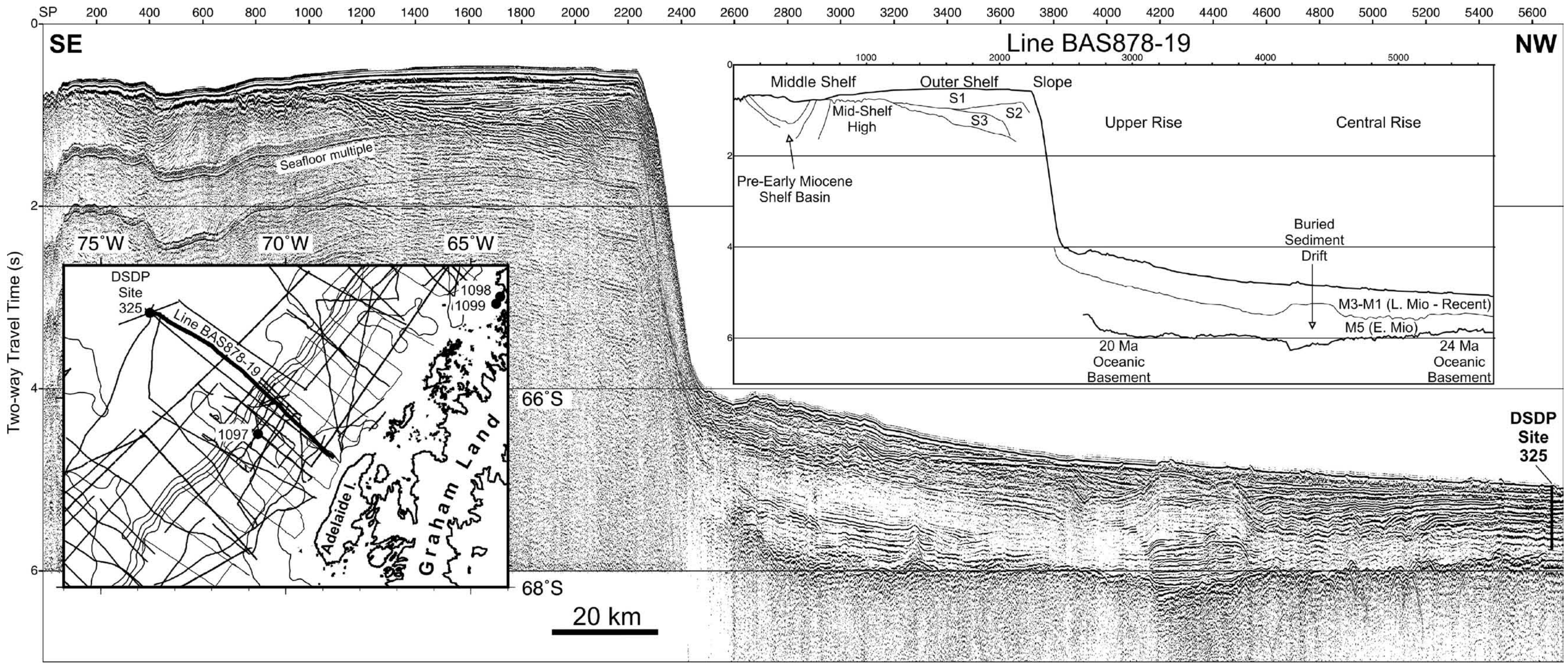
Foldout PB-1: Seismic sections from eastern Prydz Bay (Section B-B′). In the bay, Cenozoic sediments overlie Cretaceous (Surface K) and older sequences resting on basement. The shelf edge and upper slope prograded seaward through time becoming steeper. The slope and rise overlie a thick post-rift section, the latest parts of which are turbidite (inferred) and contourite (drilled) sequences deposited since the onset of glaciation. Location shown in Fig. PB-1.



Foldout PB-2: Seismic sections from western Prydz Bay (Section A-A′). The very thick post-rift section includes thick contourite (drilled) and turbidite (inferred) mounds with mudwaves in places. The upper slope comprises the Prydz Channel Fan and the shelf shows progradation but only limited topset thickness. The base of Prydz Channel Fan is Reflector A of Mizukoshi et al. (1986) and PP-12 of O'Brien et al. (2004). Location shown in Fig. PB-19.



Foldout WS-1: Seismic line NARE-8508 along the front of the Crary Trough Mouth Fan, showing fan architecture (modified from Kuvaas and Kristoffersen, 1991). Profile location is in Fig. WS-1.



Foldout AP-1: Seismic line BAS878-19 across the Antarctic Peninsula Pacific margin, showing the shelf basin, prograding wedge and continental rise sediments between the continental slope and DSDP Site 325. A buried, early Miocene sediment drift is observed beneath the central rise (Hernández-Molina et al., 2004, 2006b), but this line lies between two of the large drifts that have developed since the start of the middle Miocene (Rebesco et al., 1996, 1997, 2002). Oceanic basement ages are from Larter et al. (1997). Vertical exaggeration at the seafloor is 23:1. Inset in upper right shows an interpretation of major features. Inset in lower left shows line location.