EVOLUTION OF THE ANTARCTIC GLACIATED CONTINENTAL MARGIN

by

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A thesis submitted in conformity with the requirements
for the degree of Master of Science
Graduate Department of Geology
University of Toronto

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ABSTRACT

Evolution of the Antarctic Glaciated Continental Margin

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This thesis presents a) a critical review of existing glacial marine depositional models for the Antarctic continental margin and b) an analysis of data from Ocean Drilling Program Leg 178 (Feb.-April 1998) which drilled the Antarctic Peninsula continental margin.

Present-day 'interglacial' conditions of extensive ice shelves, severe cold, minimal meltwater production and sediment starvation on the margin are unique to Antarctica. Early work suggests such 'polar' conditions are representative of ancient Pleistocene and pre-Pleistocene environments in Antarctica. Litho- and biofacies data from Ocean Drilling Program Leg 178 provides important details regarding depositional processes responsible for glaciated continental shelf topsets and slope foresets in Antarctica. Topset deposits are constructed of deformation till reflecting large-scale subglacial reworking of pre-existing glacial and marine sediment across the shelf during ice sheet expansion and decay. Foreset deposits are composed of shelf deposits reworked downslope as debris flows and turbidity currents. Similar successions have been identified from other Pleistocene and pre-Pleistocene glacially-influenced continental margins. This work indicates that modern 'polar' conditions of Antarctica are not representative of ancient conditions.

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CHAPTER 1

INTRODUCTION

1.0 Statement of Principle Results

1.1 Background to Study

The Antarctic Ice Sheet is the largest on the planet and covers an area of approximately 13.6 million square kilometres with an average thickness of more than 2 kilometres (Barrett, 1996). The ice sheet is a key component of the world's climate system and has a major influence on global sea levels. The Cenozoic history of the ice sheet and its depositional history are poorly constrained. Attempts have been made to reconstruct the history of the ice sheet over the last 40 million years using indirect proxy data, such as oxygen isotope data (Miller et al., 1987; Shackleton and Kennett, 1975), sea level onlap/offlap curves (Haq et al., 1987) and the record of ice-rafting from the southern oceans (Erhmann, 1991). These methods have had limited, and often contradicting results due to the influence of Northern Hemisphere ice sheets on oxygen isotope data and the questionable validity of global sea level curves and inferred glacioeustatic fluctuations (Burton et al., 1987; Miall, 1986; Underhill, 1991; Miall 1992; Miall 1994).

Current level of understanding of the evolution of the Antarctic continental margin is based on over 30 years of scientific study in the region. Seismic reflection techniques provided the first regional view of the subsurface and the stratal geometry of the margin. Sedimentological ground-truthing data was provided by drilling programs that began in earnest in 1972, when Deep Sea Drilling Project (DSDP) Leg 28 drilled four holes in the western Ross Sea continental shelf (Hayes and Frakes, 1975) (Figure 1.1).

Seismic profiles of the Antarctic continental margin reveal a glaciated shelf with large-scale, flat-lying *topset* strata recording aggradation ('upbuilding') of the shelf and underlying, sea-ward dipping *foreset* strata recording progradation ('outbuilding') of the slope (Figure 1.2). These prograding *foresets* and aggrading *topsets* are thought to record advances and retreats of the ice sheet.

Most recently, the Ocean Drilling Program (ODP) Leg 178 drilled the continental shelf, continental slope and sediment drifts on the continental rise of the Pacific-facing margin of the Antarctic Peninsula (Feb.-April 1998) (Figure 1.1). Leg 178 had the objective of improving the understanding of Antarctic paleoclimates and the evolution of the continental margin. Important paleoenvironmental data is contained in diamictite facies recovered from continental shelf *topsets* and underlying continental slope *foresets*. The importance of the diamictite facies in interpreting paleoenvironment and depositional processes prompted reexamination of ODP Leg 119 cores from Prydz Bay, Antarctica (Figure 1.1) which drilled shelf *topsets* and slope *foresets* from the continental margin in 1988.

This brief description of the chapter presents tectonic setting and glacial history of the Antarctic continental margin.

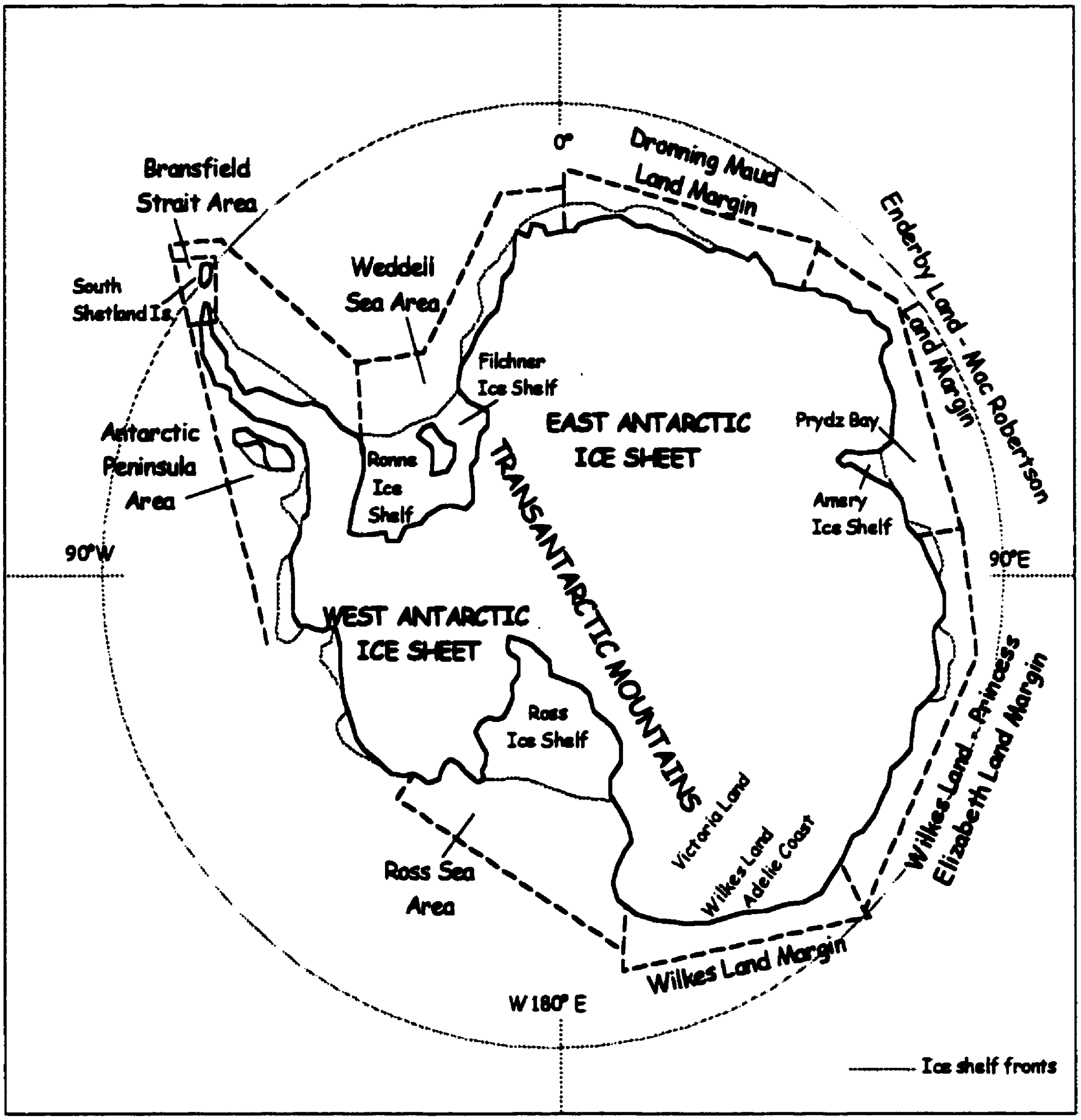


Figure 1.1. Index map of Antarctica for regions discussed in text.

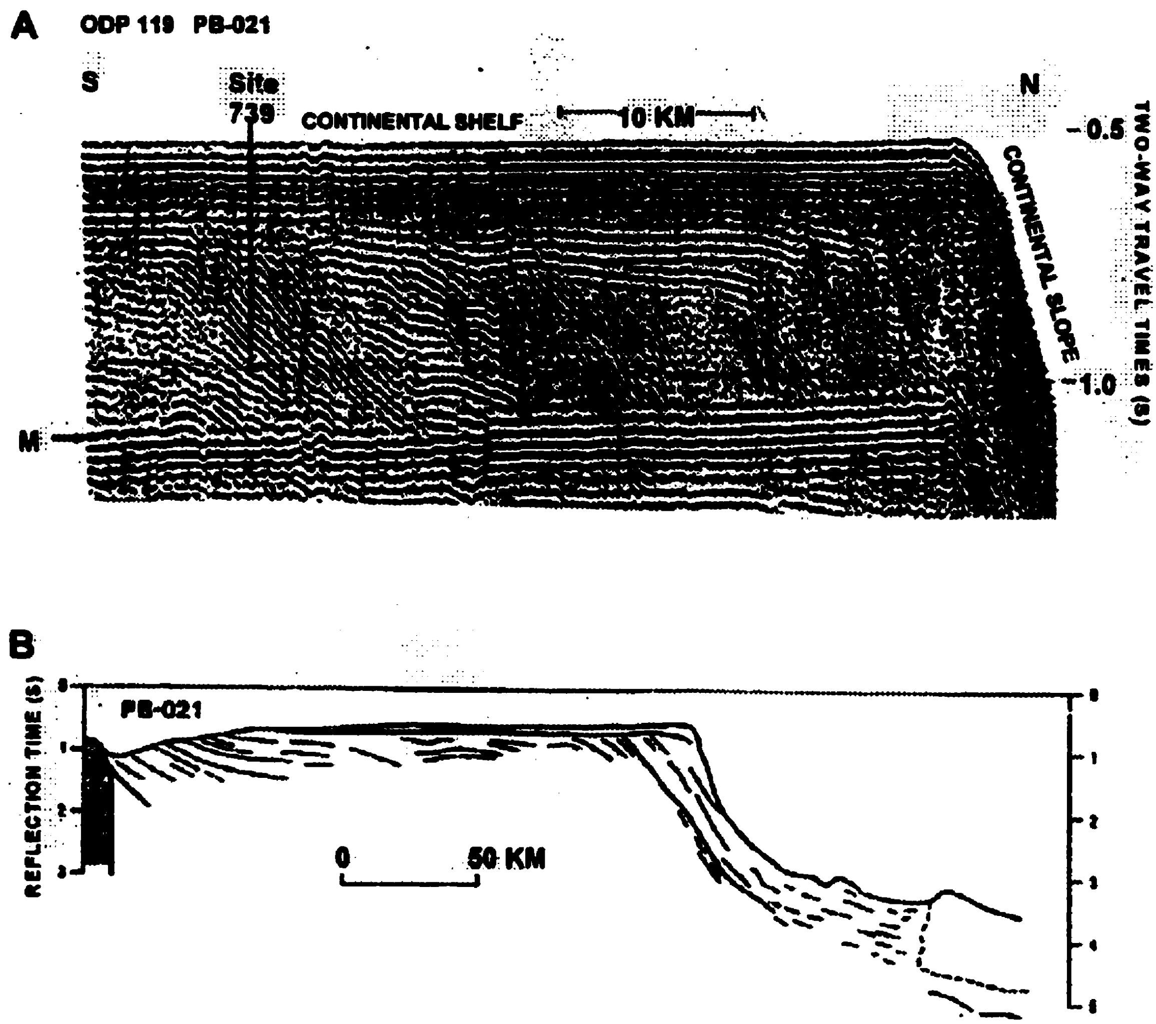
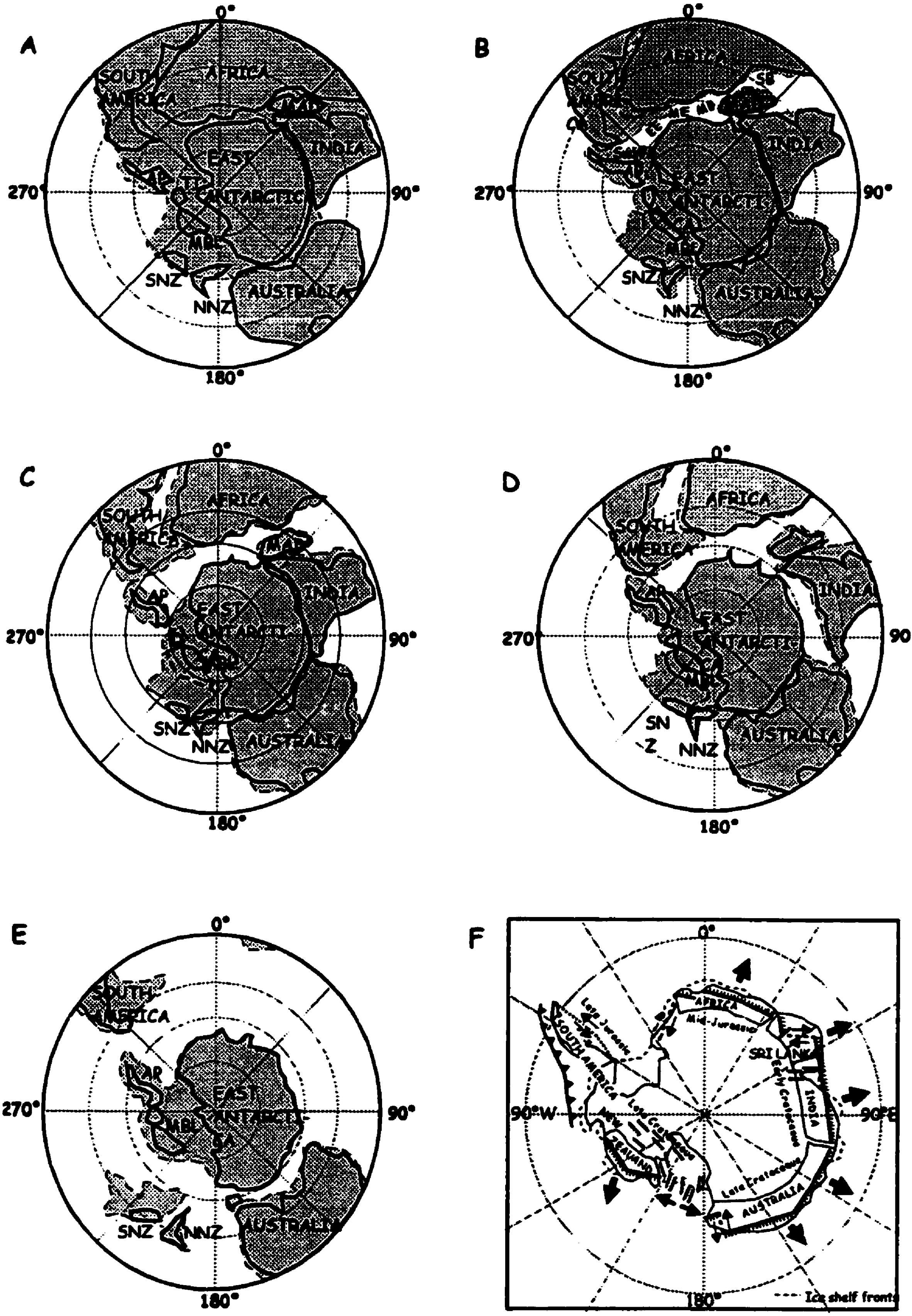


Figure 1.2. A. Representative seismic profile of the continental shelf and slope of Antarctica from Prydz Bay (ODP-119, PB-21) and B. interpretative line drawing. Note the flat-lying topset reflectors underlain by seaward dipping foreset reflectors (from Cooper et al., 1991). Location of ODP core Site 739 is indicated. This site drilled through shelf topsets and paleoslope foresets. M: multiple.

1.1.1 Tectonic setting

Reconstruction of an early Mesozoic Gondwana indicates that most of the present day margin of Antarctica was bound by other continental masses (Figure 1.3A). The break-up of Gondwana formed the passive continental margins of Antarctica. Starting in the south-western Weddell Sea, extension began in the back-arc basin of the mid to late-Jurassic Rocas Verdes Basin of South America (Lawver et al, 1991) (Figure 1.3B). Jurassic rifting in the Weddell Sea proceeded clockwise around East Antarctica to separate Dronning Maud Land from Africa and South America (130 Ma) (Figure 1.3C), Enderby Land-Queen Mary Coast and Prydz Bay from Sri Lanka and India (127-118 Ma) (Figure 1.3D), Wilkes Land from Australia and finally New Zealand and Marie Byrd Land (85-95 Ma) (Figure 1.3E), (Lawver et al, 1991; Behrendt & Cooper, 1991). Active rifting is occurring today in the Ross embayment of West Antarctica.

With the exception of a small portion of the Pacific-facing margin of the Antarctic Peninsula, all the continental margins of Antarctica are either rifted passive margins or sheared transform margins (Figure 1.3F). The Pacific-facing margin of the Antarctic Peninsula was, and continued to be, a convergent margin up until very recently (3-4 Ma). This subduction was active before the break-up of Gondwana and continued as other portions of the landmass rifted apart. Since the end of active plate convergence, sediments have been preserved as the margin has subsided (Bart and Anderson, 1995).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Late Jurassic
SOUTH AMERICA
SRI LANKA
Early Cretaceous
INDIA
Late Cretaceous
ZEALANDIA
AUSTRALIA
90°W
90°E
180°
Ice shelf fronts

Figure 1.3. Mesozoic reconstruction of Gondwana (Lawver et al. 1991). A: MAD, Madagascar; AP, Antarctic Peninsula; TI, Thurston Islands; MBL, Marie Byrd Land; SNZ, south New Zealand; NNZ north New Zealand. Continental blocks are reconstructed to a fixed East Antarctica. The Antarctic Peninsula has been rotated with respect to East Antarctica. B: 140 Ma reconstruction of West Gondwana (South America-Africa) and East Gondwana. Seafloor spreading has taken place in the Somali Basin, Mozambique Basin and south-western Weddell Sea. A sheared transform margin is present along the Explora Escarpment. SB, Somali Basin; MB, Mozambique Basin; SwWS, south-western Weddell Sea; ME, Mozambique Escarpment; EE, Explora Escarpment. C: 130 Ma reconstruction of Gondwana. Rifting has started in the South Atlantic between South America and Africa producing a reorganization of the seafloor spreading in the Weddell Sea at 132 Ma; D: 118 Ma reconstruction of Gondwana. Rifting between India and Antarctica has begun with the cessation of seafloor spreading in the Somali Basin. West Antarctica, with the exception of Marie Byrd Land, has assumed its present-day geographical location with respect to East Antarctica. E: 70 Ma reconstruction of Gondwana. Stretching between Marie Byrd Land and East Antarctica has produced the Antarctic continental mass as it is presently configured. Rifting between Australia and Antarctica has begun as well as rifting between south New Zealand and Marie Byrd Land. F: Summary chart of present-day Antarctica showing the continental blocks that rifted off Antarctica and the time of rifting.

1.1.2 Physical setting

The Antarctic continental shelf has a so-called 'reverse morphology' where water depths across the inner shelf are greater (troughs up to 1500m deep) than that at the shelf edge (200-400 m deep) (ten Brink et al, 1995; Rebesco et al., 1998) (Figure 1.4). This morphology is characteristic of glaciated margins and is not observed on non-glaciated low-latitude margins. It is generally accepted that the 'reverse morphology' is a consequence of glacial over-deepening of the inner shelf by fast flowing ice streams (Hughes, 1987; ten Brink et al., 1995). In addition, water depths across the Antarctic shelf are generally greater than that of mid- and low-latitude shelves suggesting continued subsidence of the Antarctic margin since the onset of Cenozoic glaciation (Elliot, 1985; Hambrey et al., 1991). Areas of the margin differ with regard to when rifting took place and this should affect the amount of vertical movement that each area has experienced over the course of Cenozoic glaciation.

Subsidence along a passive margin is generally regarded as a four stage process. Initial synrift subsidence due to crustal extension during rifting is then followed by thermal uplift from aesthenospheric upwelling associated with the rifting process. Following rifting there is a period of postrift tectonic subsidence as the margin cools. This postrift subsidence may be amplified by additional subsidence from sediment loading (Reid, 1989). Similarly, glacial erosion may promote uplift (Molnar and England, 1990).

Since rifting occurred relatively early along the Prydz Bay margin of Antarctica (~127 Ma) it is expected that residual thermal subsidence has been small since the onset of glaciation (~ 40 Ma). In contrast areas of the Pacific-facing margin of the Antarctic Peninsula underwent subduction, from 30 Ma ago in the south to 4 Ma in the north and has therefore experienced a different subsidence history. This history is not well constrained.

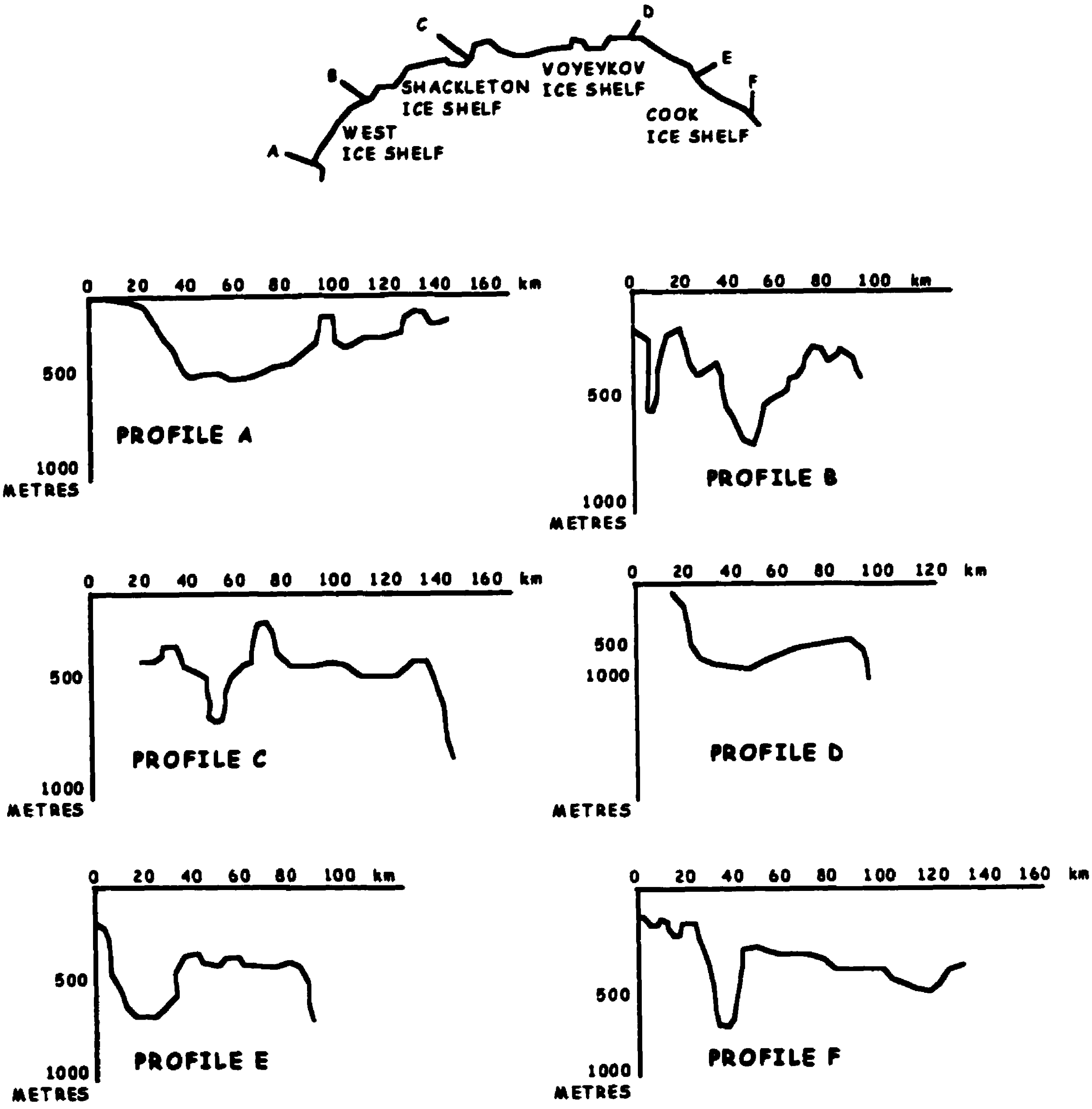

Figure 1.4. Representative depth profiles across the East Antarctic continental shelf (from Domack and Anderson 1983) showing typical rugged topography. Note the deep depression that occurs on the inner shelf that produces the 'reverse morphology' of the shelf.

1.1.3 History of glaciation

A major problem facing scientists attempting to reconstruct Antarctica's glacial history is to determine the onset of continent-wide ice cover. Drilling in the Ross Sea recovered glacial marine sediments dating back to the late Oligocene, but the proximity of the Transantarctic Mountains to these sites suggested that these glaciers were local and related to the tectonic uplift of these mountains (Barrett, 1989).

Ocean Drilling Program Leg 119 (Prydz Bay, 1988) provided key information in establishing the onset of continent-wide glaciation. The bay lies at the mouth of a sediment-filled graben structure that is related to the break-up of Gondwana. This graben may have existed since late Mesozoic time (Federov et al., 1982) or even Paleozoic time (Stagg, 1985). A large volume of East Antarctic ice currently drains through the graben and Prydz Bay therefore was expected to reveal one of the earliest indications of continent-wide ice reaching the coast. Drilling confirmed through paleontological evidence that continent-wide glaciation had commenced by earliest Oligocene time and possibly during the mid- to late Eocene.

The initiation of a continent-wide ice sheet was followed by periods of ice sheet expansion and contraction. Evidence of this is seen in sediment cores from the Ross Sea (McGinnis, 1981; Pyne et al., 1985; Barrett, 1986; Barrett, 1989), Prydz Bay (Hambrey et al., 1991), in seismic profiles from the Antarctic Peninsula (Bart and Anderson, 1995; Larter and Barker, 1989; Larter and Cunningham, 1993), and in sediment cores from the Antarctic Peninsula (Barker et al., 1999; Anderson, 1999). However, the timing of these events and their relationship to the much better-studied glacial and interglacial deposits of the Northern Hemisphere ice sheets is very poorly constrained. Depositional models are also limited by few sedimentological data.

1.2 Research Objectives

The main objectives of the thesis are:

1) to present a critical review of existing depositional models for the Antarctic continental margin and to highlight gaps in our current understanding of the evolution of the margin;
2) to reconstruct paleoenvironments and depositional processes on the Antarctic Peninsula shelf and slope using recent ODP Leg 178 data by intergrating biofacies and lithofacies data;

1.3 Method

The sedimentological and paleontological data presented as Chapter 3 of this thesis were acquired by the scientific staff on board the JOIDES *Resolution* during Leg 178 (Feb.-April 1998) Antarctic Peninsula. Facies analysis techniques similar to those used on ODP Leg 178 were also used by the author to reevaluate ODP Leg 119 (Prydz Bay, 1988) cores in March 1999. Cores (approx 700 m) were logged at the ODP Core Repository at the Lamont Doherty Earth Observatory at Columbia University in Palisades, New York. This reevaluation allowed a comparative analysis between the two locations and strengthened the results from Leg 178 discussed in Chapter 3. Data from

Leg 119 and the analysis of the depositional processes along the Prydz Bay margin will be augmented by additional data to be collected by the author during Leg 188 in the spring of 2000. This combined data set will be presented to the Department in the form of a PhD thesis.

Sedimentological data acquisition included:

(i) core facies analysis and description
(ii) grain size/textural analysis
(iii) thin section work
(iv) x-ray diffraction analysis
(v) seismic profile analysis
(vi) integration of lithofacies and biofacies

Sediment types were defined according to:

(i) lithology
(ii) sediment texture
(iii) association of sedimentary structures
(iv) vertical sequences of structures and lithologies
(v) biogenic structures
(vi) mineral composition

1.4 Structure of Thesis

The principle chapters of the thesis – chapters 2 and 3 – are self-contained papers that together present a comprehensive look at studies that have taken place, and are currently in progress around the Antarctic continental margin. Chapter 2 is a critical review of existing glacial marine depositional models which traces the evolution of our understanding of the sedimentological processes that have formed the present Antarctic continental margin.

Chapter 3 has been submitted to *Marine Geology* for publication. It presents and discusses results from Ocean Drilling Program Leg 178 which drilled the Pacific-facing margin of the Antarctic Peninsula (Feb.-April 1998).

Statement of co-authorship:

Chapter 2:

Cenozoic glacial sedimentation on the Antarctic continental shelf and slope: a critical review

By Nicole Januszczak

Chapter 3:

Ocean Drilling Program Leg 178 (Antarctic Peninsula): Sedimentology of glacially-influenced continental margin 'topsets' and 'foresets'

Contributing authors:

Nicholas Eyles, James Daniels, Lisa E. Osterman, Nicole Januszczak

N. Januszczak was a Shore-Based Scientist for ODP Leg 178 and is responsible for:

(i) integration of lithofacies and biofacies data from Leg 178

(ii) providing a comparative analysis with core work completed on ODP Leg 119 (Prydz Bay, 1988) cores at the Lamont Doherty Earth Observatory, ODP Repository, Columbia University, New York.

(iii) additional figure drafting

(iv) selecting and obtaining core photographs for the manuscript from the ODP curator

(v) co-writing the manuscript

(vi) preparing the manuscript for publication

Nicholas Eyles and James Daniels were Shipboard Sedimentologists on board the JOIDES *Resolution*. Lisa Osterman acted as Shipboard Paleontologist-foraminifers. In the preparation of the manuscript, Lisa Osterman prepared and edited biofacies data, James Daniels drafted figures and Nicholas Eyles and Nicole Januszczak prepared the text of the manuscript.

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CHAPTER 2

CENOZOIC GLACIAL SEDIMENTATION ON THE ANTARCTIC CONTINENTAL SHELF AND SLOPE: A CRITICAL REVIEW

2.0 Introduction

This chapter is a critical review of current understanding of glacial and glacial marine processes which control sedimentation and facies distribution on the Antarctic continental shelf. Depositional models published to date incorporate a variety of different information, ranging from simple ice thickness data used by Carey and Ahmed (1961) in their model of sedimentation by ice shelves, to high resolution regional seismic profiling used by Bart and Anderson (1995), and subsurface geological data from drilling projects such as DSDP, MSSTS, CIROS and ODP[1]. In addition, the scale and scope of the depositional models differ greatly, from a few square kilometres (Poultier, 1947; Robin 1953; Carey and Ahmed, 1961) to thousands of kilometres of seismic track profiles in studies done on the Antarctic Peninsula continental margin (Larter and Barker, 1989; Larter and Cunningham, 1993; Bart and Anderson, 1995). Recently, computer-generated models of the evolution of the Antarctic continental margin (ten Brink et al., 1995) utilize data from seismic studies to reconstruct margin stratal geometry.

Review of a large literature suggests that the development of sedimentary models of the continental margin has undergone four phases. The first relates to the discovery of Antarctica in 1820 and the influence on 19th century glacial geologists working in the northern hemisphere. The second phase began in the early 1970's with the acquisition of broad-scale seismic data from the Antarctic continental margin. A third phase began when deep drilling commenced onshore and offshore (DSDP, CIROS, ODP). More recently, integrated models combining both seismic and subsurface data have been

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[1] DSDP-Deep Sea Drilling Project; MSSTS-McMurdo Sound Sediment and Tectonic Studies; CIROS-Cenozoic Investigations of the Western Ross Sea; ODP-Ocean Drilling Program

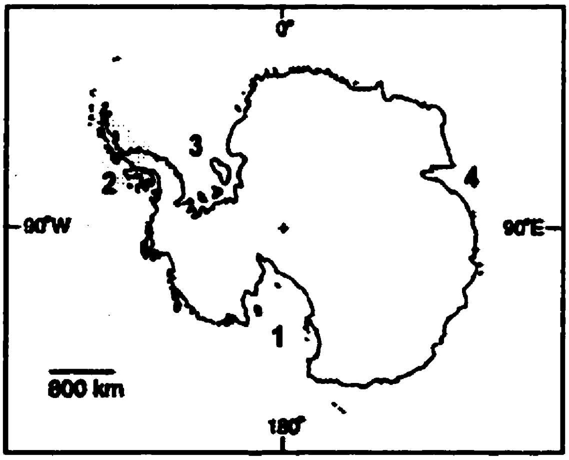
developed and reevaluation of drill core is providing useful insights. These models allow detailed comparison with northern hemisphere glaciated margins in Greenland, Norway, northwest United Kingdom and eastern Canada. Each of these phases is reviewed below. Where applicable, each section is further subdivided according to geographical location (Table 2.1). A glossary of terms is also provided (Appendix A).

Table 2.1. Organizational structure of Chapter 2.

	PHASE 2 2.2 Geophysics/ Seismic-Based Models	PHASE 3 2.3 Drilling Project Models	PHASE 4 2.4 Integrated Models A New Approach
ROSS SEA (1)	Carey & Ahmed 1961	Hayes & Frakes 1975	Fielding et al. 1997
	Alley et al. 1989	Hambrey et al. 1989	
	Anderson & Bartek 1992		
ANTARCTIC PENINSULA (2)	Larter & Barker 1989		Eyles et al. 1999 •
	Larter & Cunningham 1993		
	Bart & Anderson 1995		
WEDDELL SEA (3)		Orheim & Elverhøi 1981	
PRYDZ BAY (4)		Hambrey et al. 1991	Januszczak et al. in prep **
MULTIPLE LOCATIONS	Drewry 1986	Anderson et al. 1983	Barker et al. 1999
NORTHERN HEMISPHERE			Greenland Clausen et al. 1998
			Norway King et al. 1998
			Canada Aksu & Hiscott 1992
			United Kingdom Stoker et al. 1991

• Chapter 3

** Results to be published following ODP Leg 188, Prydz Bay (Jan.-March 2000)



2.1 Phase 1 - The Age of Discovery

The study of Antarctic glacial geology has its roots in the early 1800's with Sir Charles Lyell (1797-1875) and the *Principles of Geology* (first published in 1830-33). The discovery of Antarctica by Nathaniel Palmer in 1820 and reports of a vast, ice-bound southern continent surrounded by iceberg-infested waters had a profound influence on Lyell. Recognition that the Earth had experienced multiple glaciations is attributed to Louis Agassiz (1837; 1838) but there was little agreement as to the causes of climate change or how the widespread glacial sediments of the last glaciation had been deposited. James Croll (1821-1890) was a proponent of the astronomical theory of ice ages and proposed that changes in the eccentricity of the Earth's orbit were sufficiently great to account for every extreme climatic change evidenced by geology. This provided a mechanism for multiple glacial epochs and alternating warm and cold periods in each hemisphere. In other words, when the northern hemisphere was experiencing an ice age, the southern hemisphere would be in an interglacial period.

Lyell noted this flaw in Croll's theory and proposed that the driving force of climate change was continuous changes in the distribution of land and sea. Antarctica was used as a direct analogue, and he produced maps that appear in all eleven editions of his *Principles* which depict the current seven continents clustered near the equator to represent "extreme of heat" and then shifted to polar regions to represent "extreme of cold", even though there was no discussion of a possible mechanism to cause 'continental drift' (Fleming, 1998). Antarctica also provided a depositional model for Lyell. He introduced the term 'drift' as an umbrella term for glacial deposits which he interpreted as a product of iceberg rafting and marine submergence (Lyell, 1840). The term is still used today but only in a descriptive sense for glacial deposits.

Much glaciological work was completed in Antarctica by successive expeditions in the early 1900's, but it was not until 1961 that the first glacial depositional model was published by Carey and Ahmed.

2.2 Phase 2 - Geophysics/Seismic-based Depositional Models

2.2.1 Ross Sea

It has been over 30 years since Carey and Ahmed (1961) published their classic paper on Antarctic glacial marine sedimentation. The focus of their work was sedimentation beneath ice shelves which occupy 80% of the Antarctic coastline (Figure 2.1). Carey and Ahmed's model identified two floating glacier types in Antarctica; wet-based where the glacier slides over wet sediment and dry-based where the glacier is frozen to its substrate and moves by internal deformation (Figure 2.2). It is now recognized that although basal thermal regime is an intrinsic control on subglacial sedimentation, such environments are far too complex to categorize simply as 'dry-based' or 'wet-based' (Figure 2.2). The presence of meltwater beneath a glacier is controlled by many factors; thickness and flow of the ice sheet, geothermal heat flow, roughness of the bedrock surface, mass balance, and mean surface temperature. In this regard whilst an ice shelf is rigid and cold reflecting its dry 'polar' setting (Figure 2.2A), it can in fact be 'wet-based' where it rests on wet soft sediment (Figure 2.2B, see below). Glaciers are best described as a combination of the two glacier types proposed by Carey and Ahmed (Benn and Evans, 1998).

The next significant study in the Ross Sea area by Alley et al.(1989) described sedimentation under Ross Sea Ice Stream B (Figure 2.3). This study was based on seismic data obtained by a group of institutions, (University of Wisconsin, Ohio State University, NASA/Goddard Space Flight Centre, the University of Chicago, and others), who were conducting a cooperative glaciological and geophysical survey of the Siple Coast, the region where ice from West Antarctica drains into the Ross Ice Shelf (Figure 2.3).

Seismic surveys from Ice Stream B have shown that it is underlain by a metres-thick layer of water-saturated, unconsolidated sediment. This layer is continuous and has a smooth upper surface with the ice, but a lower surface with an angular unconformity that is eroded into flutes oriented parallel to ice flow. Alley et al. interpret this layer as deforming, water-saturated till. Further, this layer extends beneath the entire ice stream and the high velocity of the ice stream originates largely from deformation within this layer. The angular unconformity results from erosion/remobilization of soft sediment as deforming till.

The highly unconsolidated, water-saturated sediment is transported subglacially and dumped at the grounding line, leading to slumping and the development of a foreset bed composed of turbidites and debris-flow deposits (Figure 2.4). An extensive grounding line deposit tens of kilometres long and tens of metres thick forms at the terminus of the ice stream and is termed a '*till delta*' by Alley et al. (Figure 2.4).

The study of Alley et al.(1989) is significant because it indicates that the Antarctic continental margin may have experienced depositional processes not unlike those interpreted below of Pleistocene mid-latitude ice sheets. Boulton and Jones (1979) and Boulton (1996) suggested that such ice sheets rested on relatively 'soft' deformable beds give rise to a low surface profile and experienced fast ice flow or 'streaming'. Alley et al. (1989) recognized that these processes have also taken place below the Antarctic ice sheet where it rests on soft sediments.

The next significant study in the Ross Sea investigated the first deep cores from the Antarctic margin acquired by the DSDP (Deep Sea Drilling Program) in 1972 from the Ross Sea continental shelf (Figure 2.3). An important component of Anderson and Bartek's (1992) study was to identify glacial and non-glacial sedimentary successions from seismic profiles only. Particularly diagnostic features that provide evidence of glaciation are a '*foredeepening*' or 'reverse morphology' of inner shelf strata (Section 1.1.2, Figure 1.4); irregular and deep erosional troughs much deeper than typical incised fluvial valleys; and large acoustically massive sedimentary bodies or '*till tongues*' found directly on top of these glacial erosion surfaces (Figure 2.5).

On a larger scale, Anderson and Bartek (1992) identified a major erosional surface, a mid-Miocene unconformity thought to result from a fall in global sea level. A corresponding shift in the global oxygen isotope record indicates significant ice build-up on Antarctica (Shackleton and Kennett, 1975). The Miocene/Pliocene boundary marks a change from strongly progradational, where foresets have built-out from the continental margin, to stacked units of topsets recording vertical aggradation of the margin. This change is interpreted as the result of an increased frequency of glaciations during the

Plio-Pleistocene combined with higher frequency eustatic rise and fall generated by northern hemisphere glaciations. However, this same trend has been attributed to local causes by more recent, studies (Eyles et al., 1999; Bart and Anderson, 1995; ten Brink et al., 1995; see Chapter 3 below).

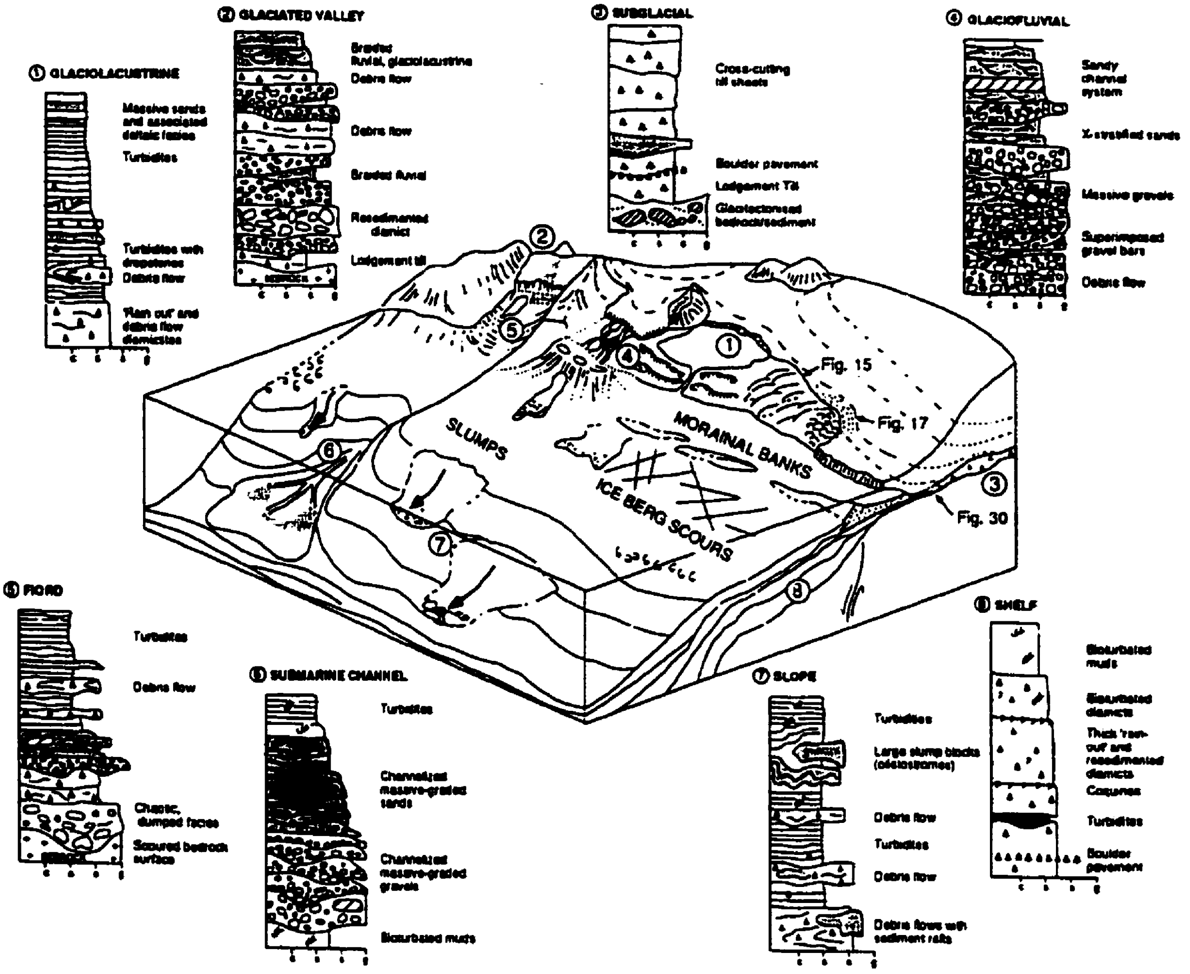
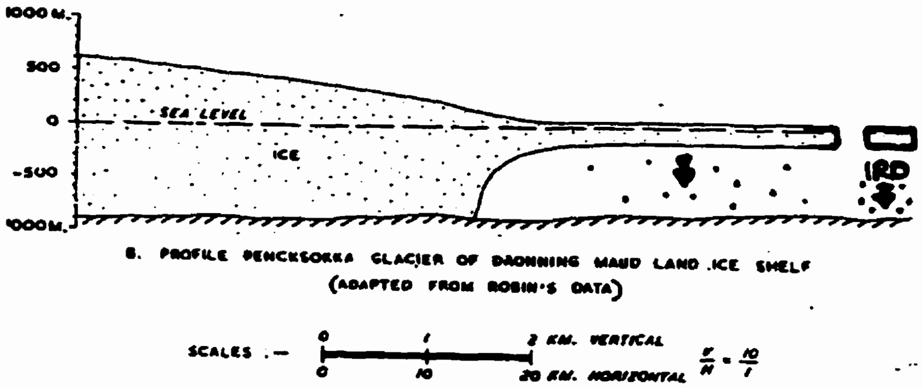
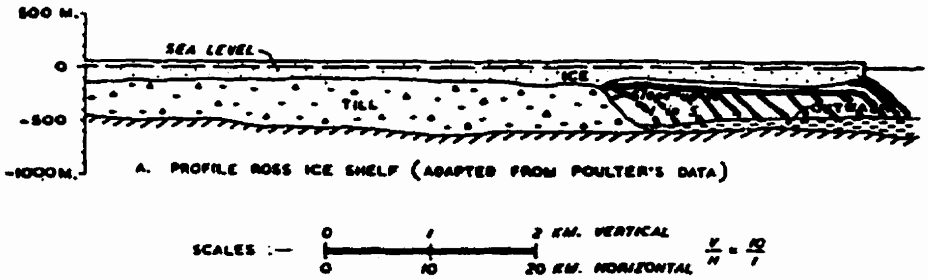


Figure 2.1. Depositional environments and typical vertical profiles of facies on a glaciated margin (from Eyles and Eyles, 1992).



A. Dry base glacier:



B. Wet base glacier:

Figure 2.2. Carey and Ahmed's (1961) depositional model for the Antarctic margin based on their identification of dry-based versus wet-based glaciers (from Carey and Ahmed, 1961).

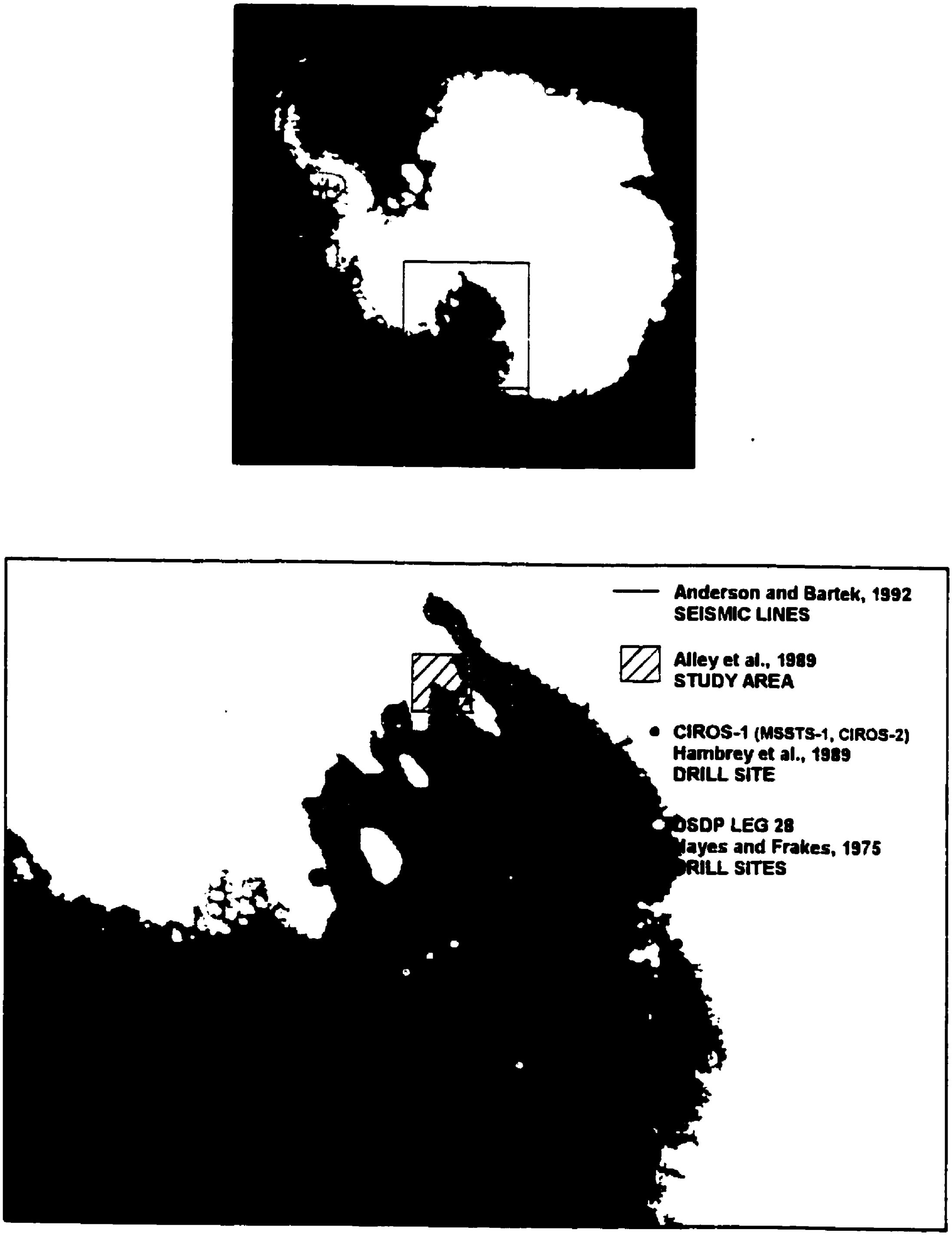


Figure 2.3. Ross Sea. Location of studies discussed in text (modified from USGS website: http://usarc.usgs.gov/antarctic_atlas).

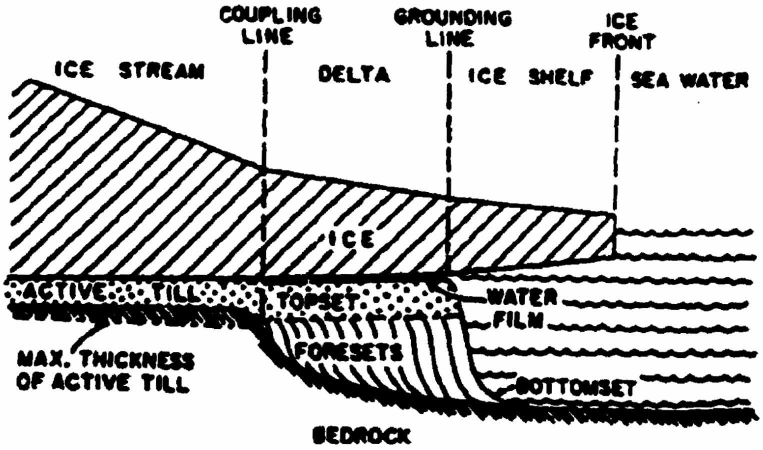


Figure 2.4. Cartoon of Alley et al.'s (1989) 'till delta' (from Alley et al., 1989).

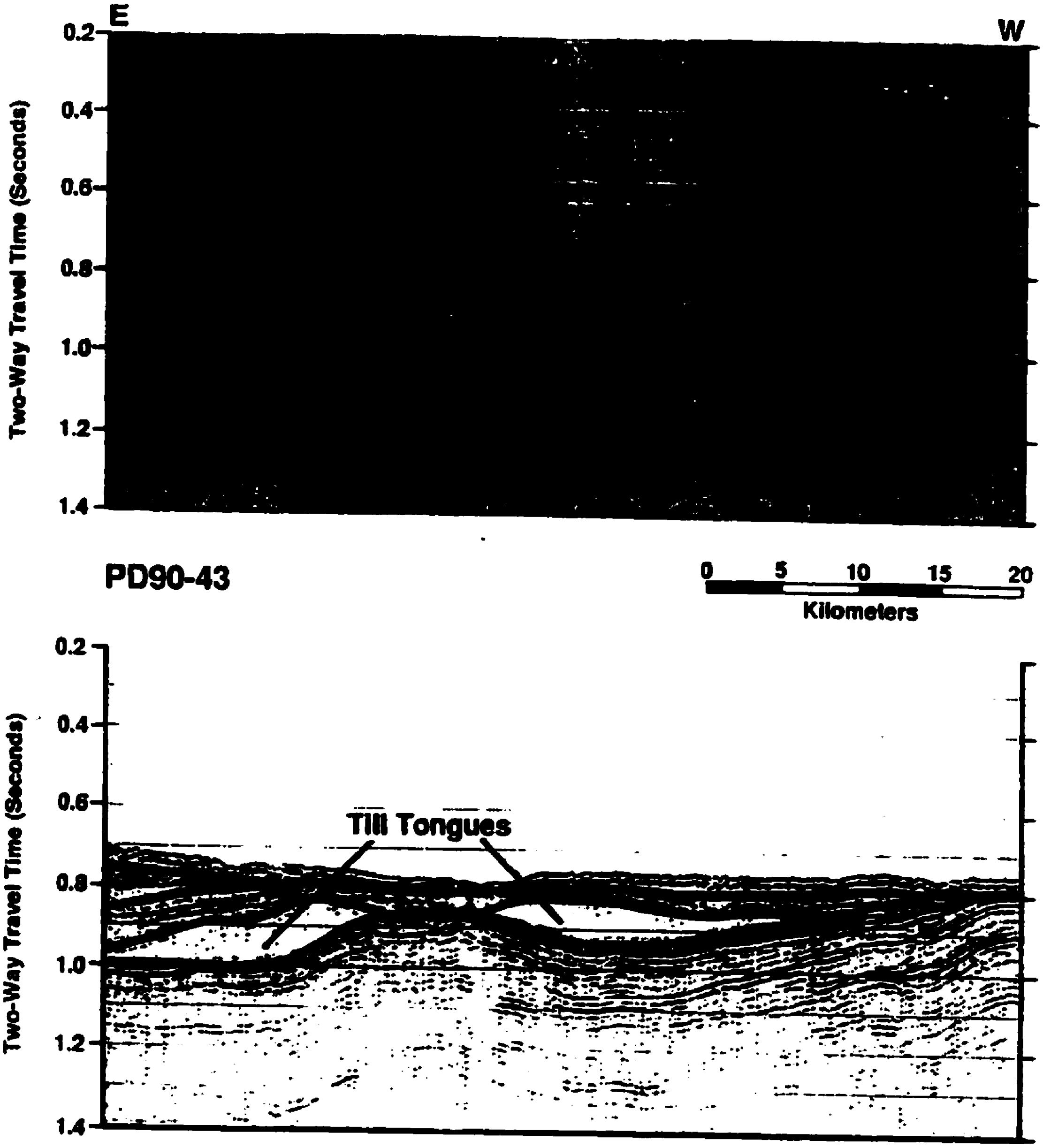


Figure 2.5. Illustration of 'till tongues' identified on seismic profiles in the Ross Sea by Anderson and Bartek (1992) (from Anderson and Bartek, 1992).

2.2.2 Antarctic Peninsula

Larter and Barker (1989) produced the first 2-D depositional model for the Antarctic Peninsula Pacific-facing margin using multi-channel seismic (MCS) profiles predominantly oriented perpendicular to the margin (Figure 2.6). MCS profiles reveal a series of oblique progradational sequences with very steeply dipping foresets. The sequence boundaries are most easily recognized where steeply dipping foresets are truncated by an unconformity at the base of an overlying topset. High seismic velocities observed in near-surface sediments are thought to be caused by compaction below grounded ice.

Their model suggests that inter-grounding sequences (IGS), composed of unconsolidated marine sediments, are deposited during periods of glacial retreat and result in aggradation of the continental shelf (Figure 2.7 A,D). During ice sheet expansion to the shelf edge basal till is deposited and IGS are eroded and transported in subglacial debris zones to be deposited in a grounding subsequence (GS) at the shelf edge and slope (Figure 2.7 B,C). This very simple climate-driven model for the evolution of the Antarctic continental margin was characterized by Larter and Barker (1989) as a 'line-source' model because deposition occurs along a broad front at the grounding line (see below).

Larter and Cunningham (1993) built on their 'line-source' concept with a 3-D model based on MCS from the Pacific-facing margin of the Antarctic Peninsula (Figure 2.8). They emphasized that their 'line-source' model for progradation of the Antarctic glaciated margin contrasts with models of progradation for low latitude margins where prograding sequences are the result of river deltas building out as 'point-sources' to the shelf edge (Posamentier and Vail, 1988) (Figures 2.8, 2.9) producing a lobate continental margin (Miall, 1979).

The validity of the 'line-source' models of Larter and Barker (1989) and Larter and Cunningham (1993) was challenged by Bart and Anderson (1995) who constructed a 2-D depositional model for the evolution of the Pacific-facing margin of the Antarctic Peninsula using *strike*-oriented seismic profiles (Figure 2.6). The use of strike-oriented profiles allowed Bart and Anderson to identify glacial unconformities and lateral variation in geometry of seismostratigraphic units and seismofacies along the continental margin. (Figure 2.10). The recognition of lateral variability is significant in that it refutes the simple 'line-source' depositional models described above that were based exclusively on seismic *dip* profiles. Bart and Anderson also pushed back the date of onset of glaciation in the Antarctic Peninsula region to the mid-Miocene with identification of glacial unconformities *below* the Plio-Pleistocene units which Larter and Barker interpreted as a record of the onset of glaciation in the region.

Figure 2.6. Antarctic Peninsula. Location of studies discussed in text (modified from USGS website: http://usarc.usgs.gov/antarctic_atlas).

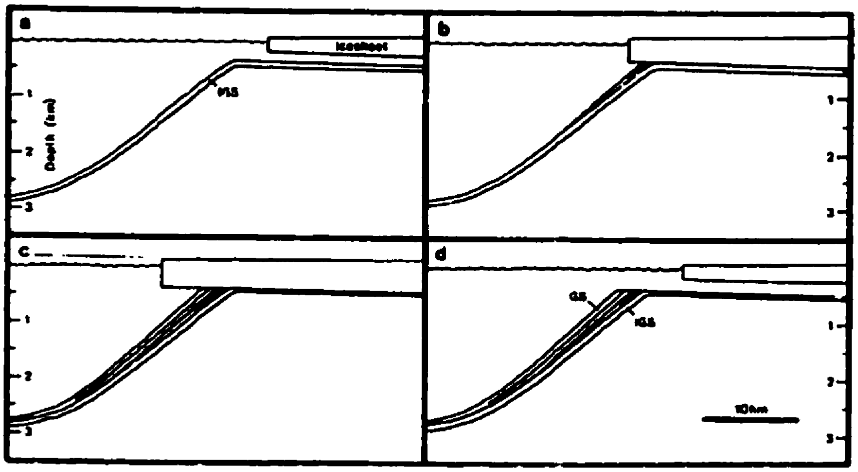
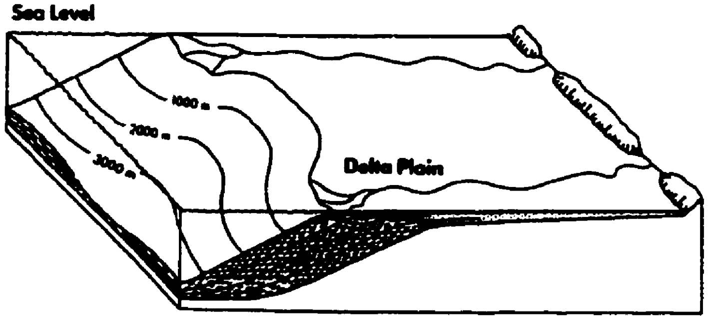


Figure 2.7. Larter and Barker's (1989) depositional model for margin evolution. IGS: intergrounding subsequence; GS: grounding subsequence. See text for discussion (from Larter and Barker, 1989).

A. Low-Latitude Prograding Margin



B. Polar Prograding Margin

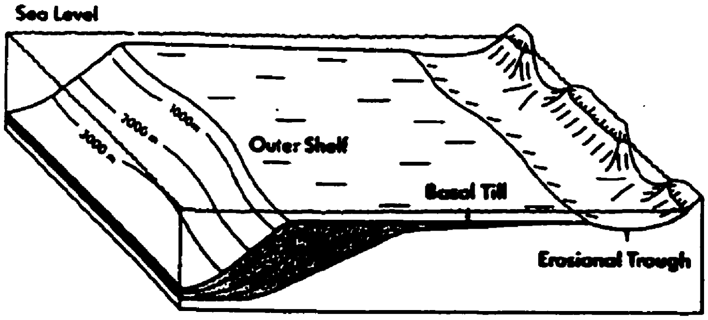


Figure 2.8. Block diagrams of models for prograding continental margins differentiating between A) a low-latitude margin and B) a 'polar' margin (from Larter and Cunningham, 1993).

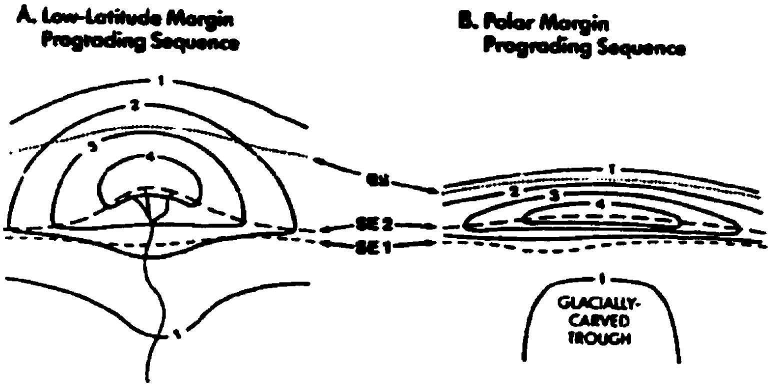


Figure 2.9. Larter and Cunningham's (1993) idealized isopach maps of continental margin prograding sequences. BS: approximate base of slope; SE1 and SE2 are shelf edge positions at the start and end of deposition respectively (from Larter and Cunningham, 1993).

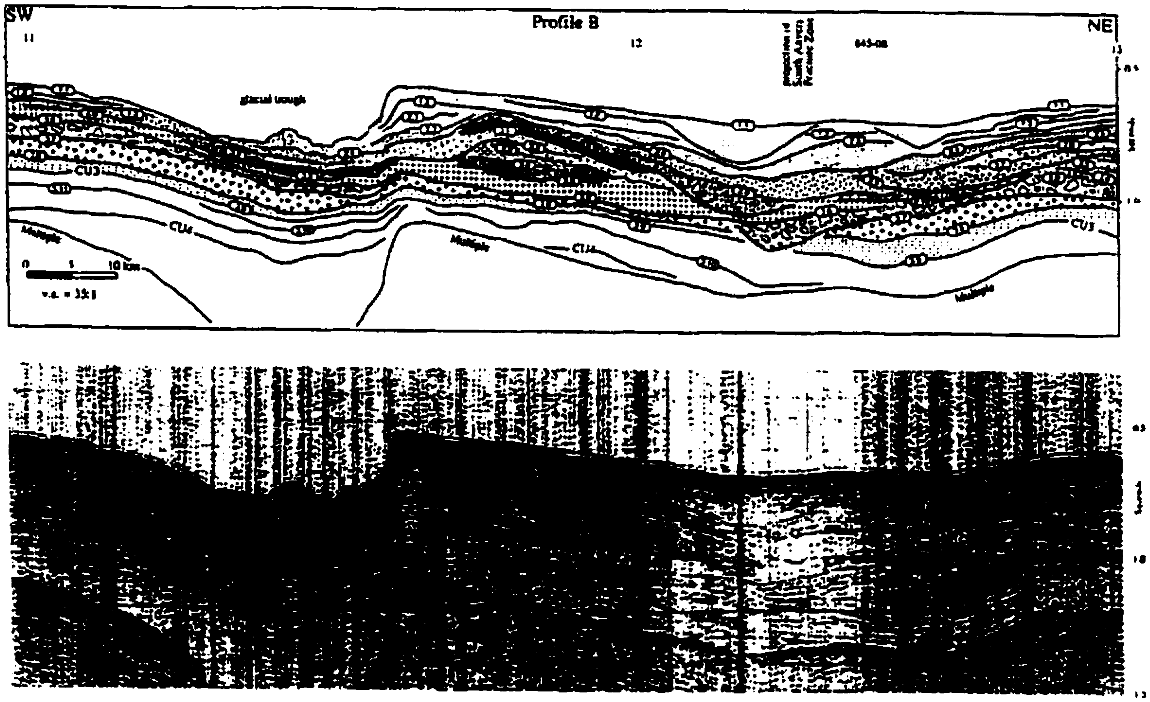


Figure 2.10. Seismic profile and interpretive line drawing of strike-oriented seismic Profile B from Bart and Anderson (1995). Lateral continuities of glacial unconformities are poor.

2.2.3 Multiple Locations

In contrast to the above models which used MCS profiles, Drewry (1986) used radio echo-sounding data from around the Antarctic continental margin to construct a depositional model for ice shelves. His model focuses on sedimentation at the grounding line where basal melting releases diamictites as 'lodgement' or 'melt-out' tills (Figure 2.11A). Sedimentation from the basal debris zone is intimately linked with melt rate. Strong melting close to the grounding line will remove all basal debris within the first tens of kilometres of ice shelf. Outer shelf glacial marine sediments are subject to downslope slumping and sliding and are therefore characterized by mass flow deposits that grade seaward into fine-grained turbidite sequences (Figure 2.11B).

The next major advance in understanding sedimentation and stratigraphic evolution along the Antarctic continental margin was generated by computer modeling. Topset stratal geometry observed in the geophysical studies of (Alley et al., 1989; Larter and Barker, 1989; Larter and Cunningham, 1993; Bart and Anderson, 1995) was successfully mimicked by a series of computer models by ten Brink et al. (1995). The model changed the relative weighting of variables such as water depth, sediment supply, subsidence rates and sea level variables for successive runs of the model and observed the resulting stratal geometry. The models suggest that the current shelf has evolved gradually and incrementally to its present geometry by multiple glacial advances and retreats of the grounding line across the shelf (Figure 2.12). During the early stages of glaciation the continental margin is shallow enough to be controlled mostly by tectonic and eustatic influences. As the shelf deepens as a result of glacial erosion and acquires a reverse profile (see above), sediments deposited during interglacial periods are trapped in the deeper inner shelf basins. During periods of glacial advance the inner shelf is preferentially eroded and sediments are reworked. As a consequence, the shelf contains only a partial record of sedimentation on the margin. These computer models were concerned with reproducing the stratal geometry of the Antarctic continental shelf, but glaciated continental shelves from the northern hemisphere show very similar stratal geometries (see below).

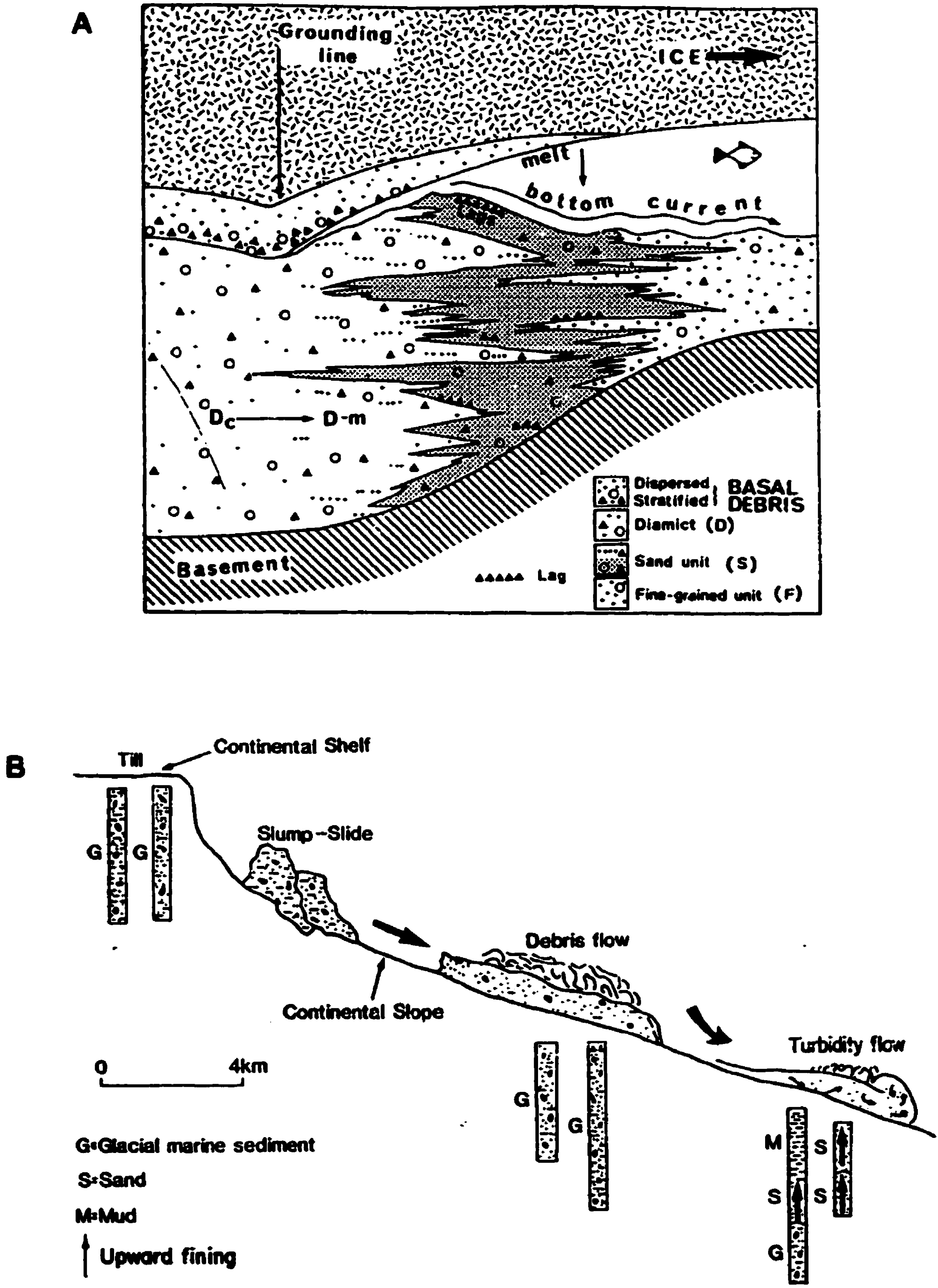


Figure 2.11. Depositional processes at A) the grounding line and B) the outer shelf and slope (from Drewry, 1986).

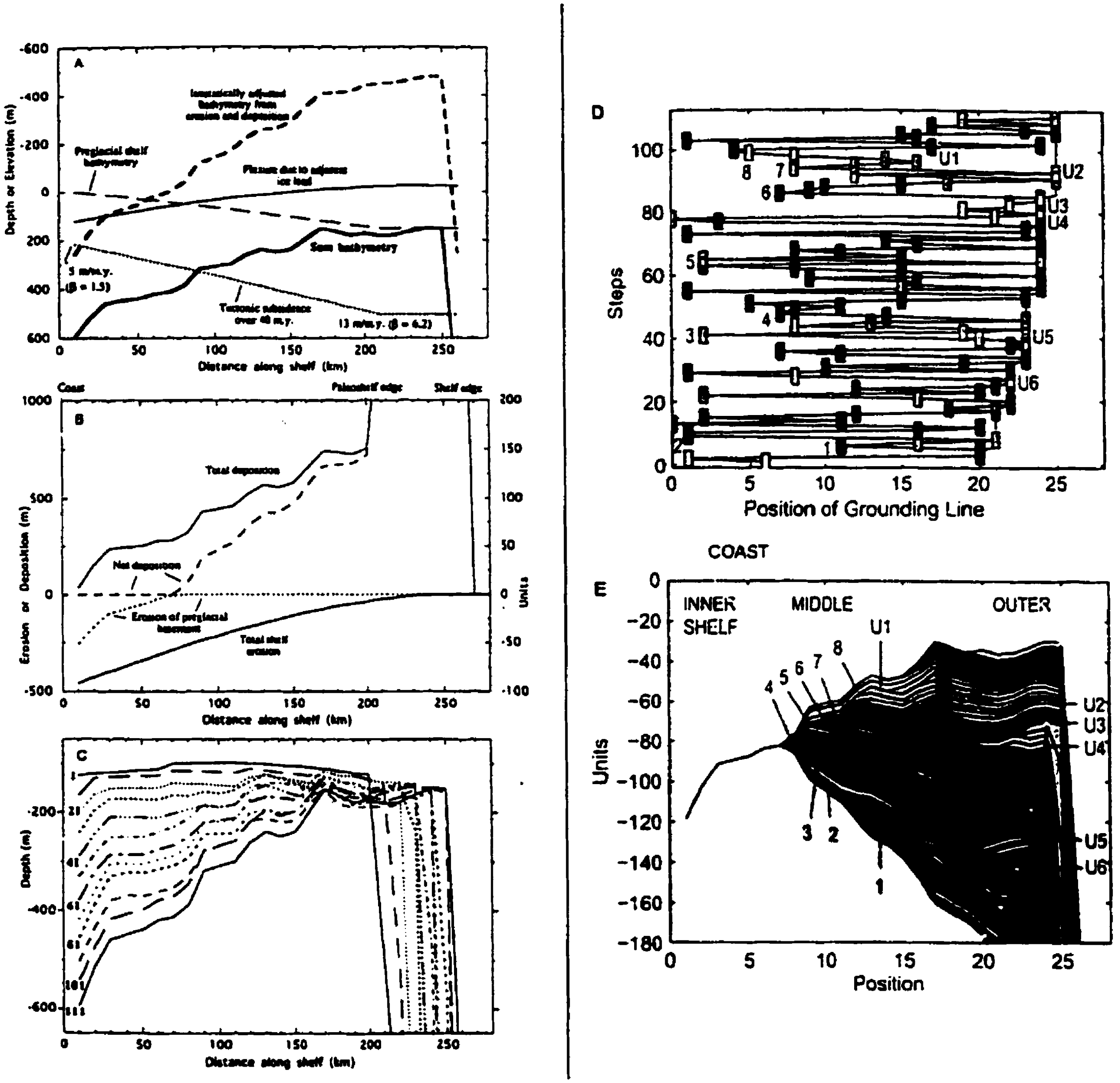


Figure 2.12. A,B,C. Computer model parameters of ten Brink et al. (1995). A) Contributions to shelf bathymetry. B) Erosion and deposition. C) Sea floor morphology after the first, tenth, twentieth, etc. steps in the model. D) Position of the grounding line and shelf edge in each steps (run has 111 steps). B) Stratigraphic section generatedby deposition and erosion relative to the positions of the grounding line. U1-U6: unconformtities. 1-8: labels for preserved layers in the middle shelf.

2.3 Phase 3 - Drill-based Depositional Models

Drilling expeditions continue to provide a very useful database of sedimentological data from the Antarctic continental margin. Due to the prohibitive expense however of drilling such a remote margin, large-scale core drilling has been restricted to the Ross Sea, Prydz Bay and the Antarctic Peninsula.

2.3.1 Ross Sea

During the austral summer months of 1972/73, Deep Sea Drilling Project (DSDP) Leg 28 drilled four holes in the Ross Sea continental shelf penetrating a maximum depth of 439 metres below sea floor (mbsf) and recovered 581 metres of core (50% recovery) (Hayes and Frakes, 1975; Figure 2.3). This was the first recovery of sediments from the Antarctic continental shelf and the first of five DSDP legs scheduled to investigate the long-term glacial history of the Antarctic. Leg 28 had the most high-latitude sites, so its results were of greater importance and since became the standard for reconstructing Antarctic Cenozoic history.

Results from DSDP Leg 28 indicated that glacial sedimentation on the Ross Sea continental shelf is largely comprised of pebbly mudstones (diamictites) interpreted by Hayes and Frakes (1975) as ice-rafted debris (IRD) (Figure 2.13). Scattered benthic foraminiferas and molluscs indicated deposition under open glacial marine conditions, however a few sampled molluscs indicated reworking. Surprisingly, the presence of subglacial deposits was only briefly mentioned. Diatomaceous intervals record marine sedimentation in seasonally open seas. A large erosional unconformity observed over most of the shelf in the late Miocene/early Pliocene is attributed to the expansion of the Ross Ice Shelf to the shelf edge and the of bulldozing of large volumes of detritus downslope.

DSDP was succeeded by MSSTS-1 (McMurdo Sound Sediment and Tectonic Study) in 1979 which drilled in western McMurdo Sound and reached 227 metres below sea floor (mbsf) and extended the glacial record back to the Oligocene (~32 Ma) (Barrett, 1986). This project was in turn, succeeded by CIROS-2 (Cenozoic Investigations in the Western Ross Sea) in 1984. CIROS-2 drilled a complex sequence of Pliocene and Quaternary ice advances and retreats (Pyne et al., 1985). The results of CIROS-1 which drilled very close to the site of MSSTS-1 will be discussed here as it had the best recovery (98%) penetrating 702 mbsf (Hambrey et al., 1989; Figure 2.3).

The most important result (and limitation) of the CIROS-1 study was the recovery and environmental interpretation of large volumes of poorly sorted diamictites. All such facies were interpreted as either subglacial or IRD and were termed: lodgement till; meltout till; basal till; waterlain till; proximal glaciomarine sediment; or distal glaciomarine sediment (Appendix A) (Figure 2.14). Hambrey et al. identified 40 distinct ice advances in the Western Ross Sea on the basis of simple interpretation of massive diamictites as till. The depositional model from CIROS-1 failed to consider other possible depositional processes for diamictites and prompted a reevaluation of CIROS-1 data by Fielding et al. (1997, see below).

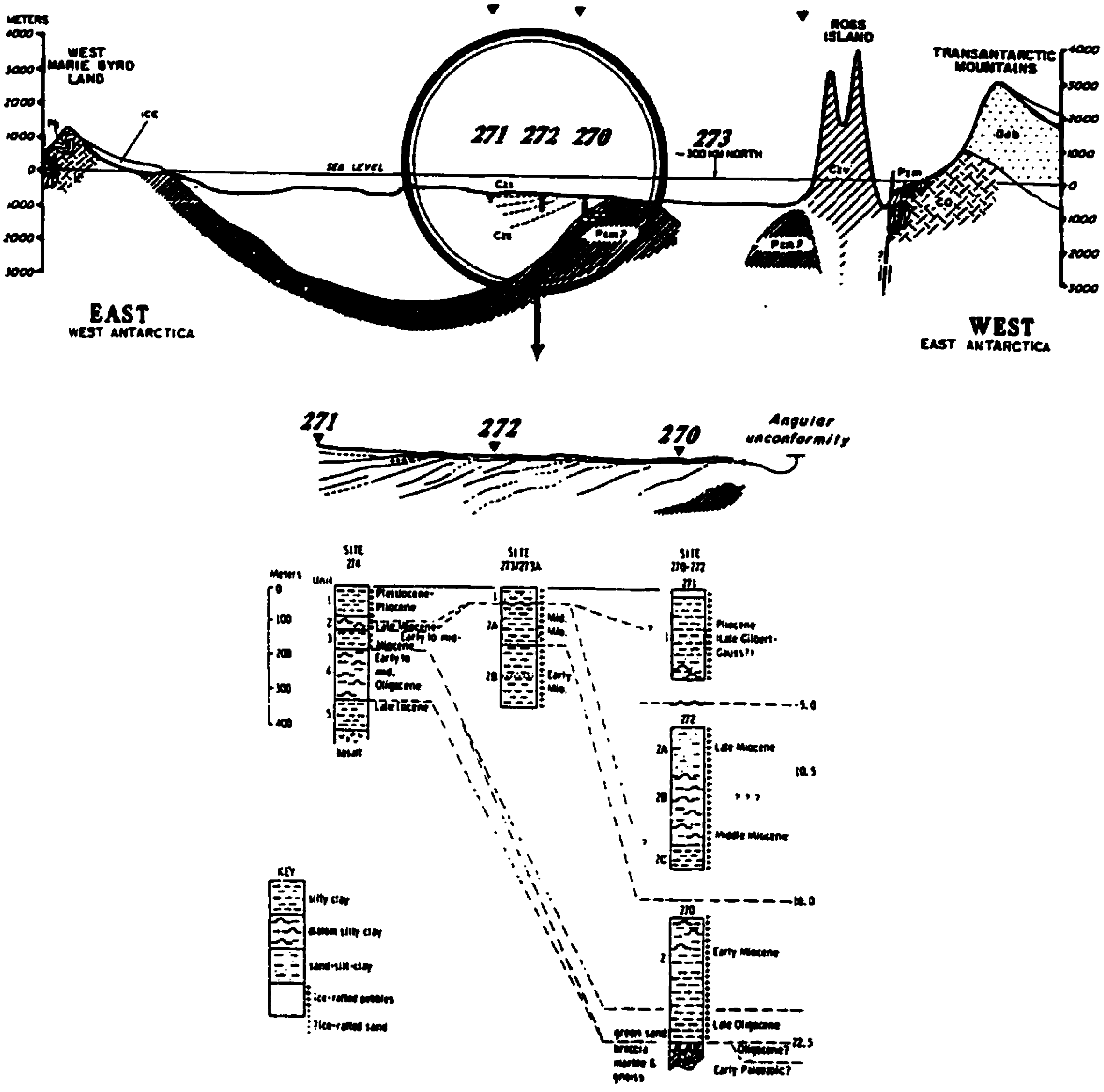
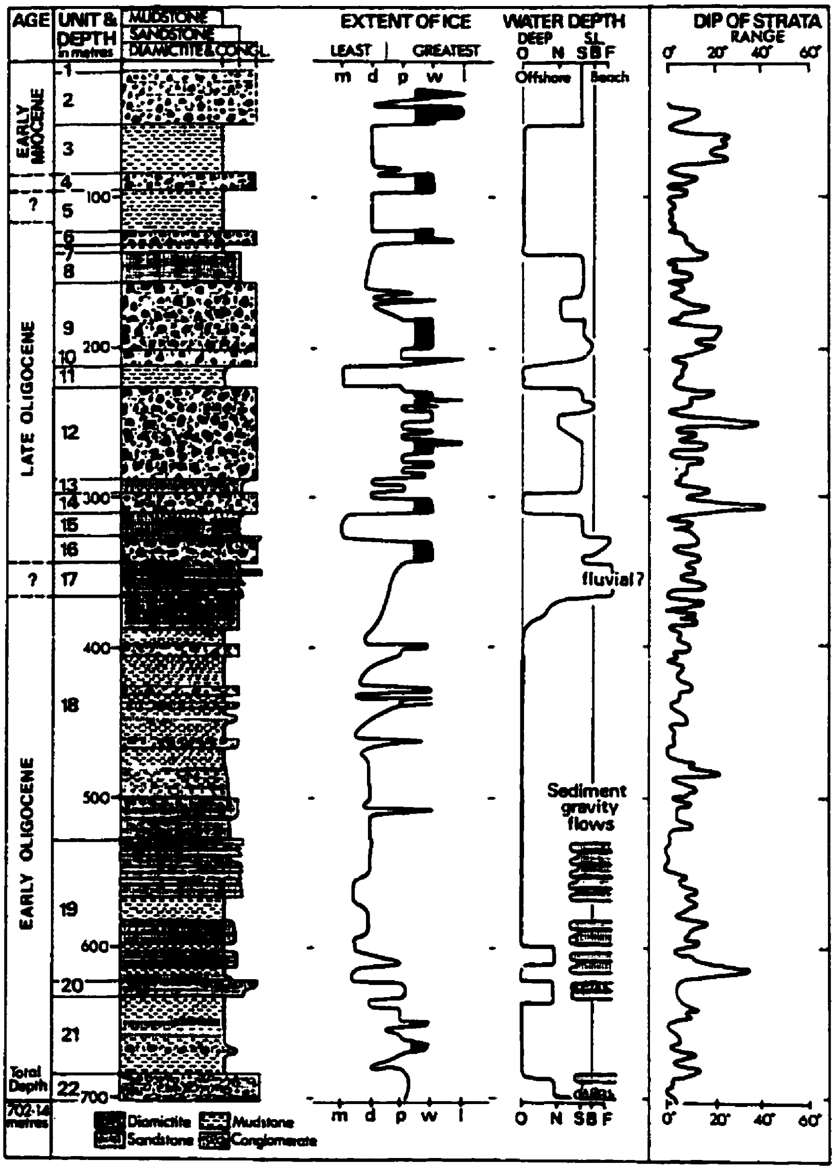


Figure 2.13. Top: Schematic structural section through DSDP shelf sites. Bottom: Stratigraphy and sedimentology of the DSDP Ross Sea sites (from Hayes and Frakes, 1975).


AGE
UNIT & DEPTH in metres
MUDSTONE
SANDSTONE
DIAMICTITE & CONGL.
EXTENT OF ICE
LEAST
GREATEST
m d p w l
WATER DEPTH
DEEP
S.L.
O N S B F
Offshore
Beach
DIP OF STRATA RANGE
0° 20° 40° 60°
EARLY MIOCENE
?
LATE OLIGOCENE
?
EARLY OLIGOCENE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
100
200
300
400
500
600
700
Total Depth 702.14 metres
fluvial?
Sediment gravity flows
Diamictite
Mudstone
Sandstone
Conglomerate

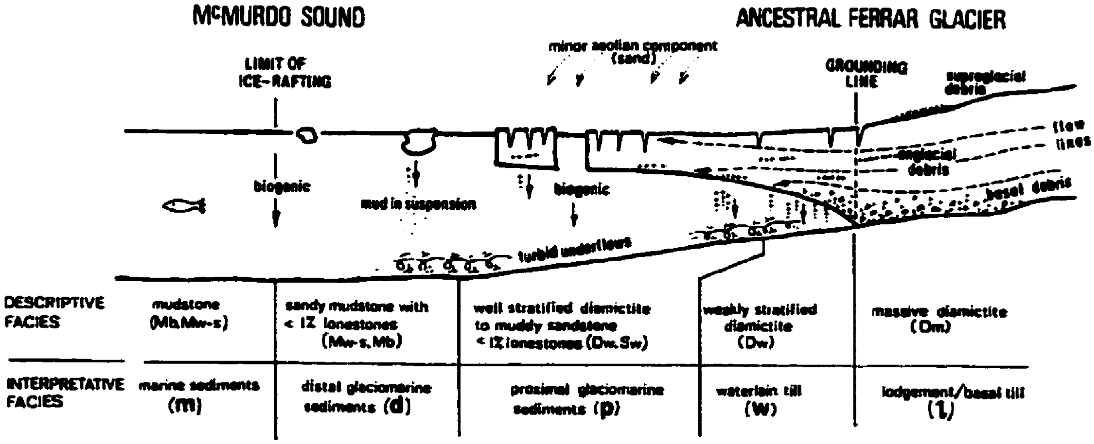

McMURDO SOUND
ANCESTRAL FERRAR GLACIER
LIMIT OF ICE-RAFTING
minor aeolian component (sand)
GROUNDING LINE
supraglacial debris
flow lines
englacial debris
basal debris
biogenic
mud in suspension
biogenic
turbid underflows
DESCRIPTIVE FACIES
mudstone (Mb,Mw-s)
sandy mudstone with < 1% lonestones (Mw-s,Mb)
well stratified diamictite to muddy sandstone < 1% lonestones (Dw,Sw)
weakly stratified diamictite (Dw)
massive diamictite (Dm)
INTERPRETATIVE FACIES
marine sediments (m)
distal glaciomarine sediments (d)
proximal glaciomarine sediments (p)
waterlain till (w)
lodgement/basal till (l)

Figure 2.14. Top: Summary lithologic log of the CIROS-1 drill core with interpretation of extent of ice and water depth. Bottom: Depositional model for sedimentation from the CIROS-1 drill core (from Hambrey et al., 1989).

2.3.2 Weddell Sea

The Weddell Sea is surrounded by 100km-wide ice shelves on the eastern side and the Filchner and Ronne Ice Shelves to the south (Figure 2.15). The Norwegian Antarctic Research Expedition (NARE 1978/79) collected shallow gravity cores, grab samples, water samples, underwater photographs, shallow seismic reflection profiles and side-scan sonar records from the eastern Weddell Sea.

Orheim and Elverhøi (1981) used this data to characterize the sedimentary environment of the eastern Weddell Sea as sediment 'starved'. Starvation results from glacial sediment being released and trapped below ice shelves. Because little meltwater is produced under present 'polar' climate conditions, little sediment escapes onto the continental shelf. In situ bioclastic sedimentation predominates in the inner shelf areas and ice rafted debris (IRD) is deposited on the outer shelf and slope. Low sedimentation rates on the shelf are also suggested by organic oozes that cover the seafloor and well-preserved iceberg plough marks on the shelf.

Overconsolidated pebbly muds recovered from the shelf break are interpreted as basal till deposits and bioclastic content in these tills indicate that marine sediments were reworked during during earlier episodes of glacial advance. Basal tills are overlain by sediments which were frozen into the ice shelf during periods of ice shelf grounding, but subsequently melted out during retreat. Advance and retreat of the grounding line causes a complex interbedding of sediments (Figure 2.16).

This depositional model of a margin 'starved' of sediment is a characteristic of a 'polar' glacial model where glacial marine deposits are interpreted within the context of the current dry and cold conditions on Antarctica. However the identification of glacially reworked sediments implies episodes of deformation below the ice sheet and transport as deformation till (see Chapter 3). Large fluxes of till across the shelf during periods of glacial advance contradict the model of polar starvation.

Figure 2.15. Weddell Sea. Location of studies discussed in text (modified from USGS website: http://usarc.usgs.gov/antarctic_atlas).

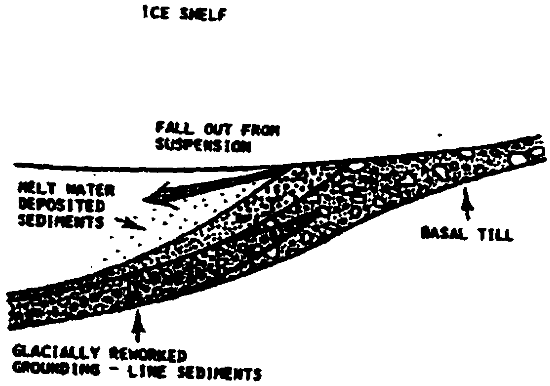


Figure 2.16. Sediment 'starved' model from Orheim and Elverhøi (1981). Deposition at the grounding line.

2.3.3 Prydz Bay

In 1988 Ocean Drilling Program (ODP) Leg 119 drilled through continental shelf topsets and slope foresets in Prydz Bay penetrating 487 mbsf and averaging 36% recovery (Figure 2.17). Prograding foresets were interpreted by Hambrey et al. (1991) as the result of ice reaching the edge of the continental shelf and depositing 'waterlain' till. Repeated ice advances deposited gently dipping prograding slope sequences. During periods of glacial advance flat-lying topsets are deposited beneath the grounded ice sheet as lodgement tills.

As noted with the above interpretation of diamictites from CIROS-1, the wider applicability of Hambrey et al. (1989; 1991) is weakened by simplistic analysis of massive diamictite as subglacial till (Figure 2.18). As knowledge of diamictite-forming processes on glacial and non-glacial continental margins has expanded (Eyles, 1993) it is evident that massive diamictite facies are deposited by a wide range of processes. Re-examination of Leg 119 cores by the author shows that 'waterlain till' and 'lodgement till' of Hambrey et al. (1991) are better interpreted as debris flows. This is in keeping with recent models of a soft-bed under fast-flowing ice streams resulting in deposition of deformation till on the shelf and the release of such debris downslope at the shelf edge to form foresets (see Chapter 3). This model will be tested by the author during ODP Leg 188 in early 2000 which will drill the Prydz Bay continental margin. Leg 119 and 188 data will be integrated and presented as a PhD thesis by the author.

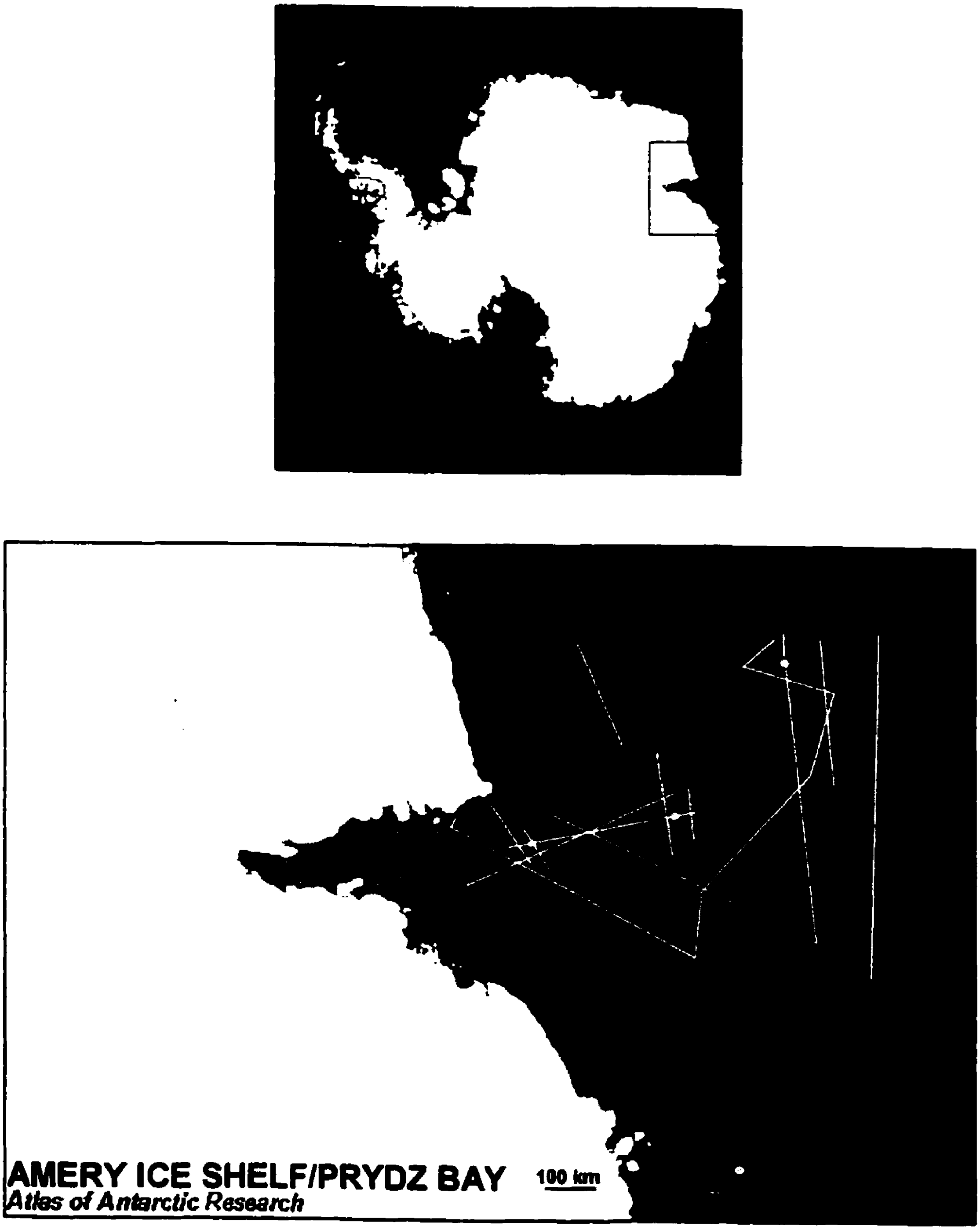


Figure 2.17. Prydz Bay. Location of studies discussed in text (modified from USGS website: http://usarc.usgs.gov/antarctic_atlas).

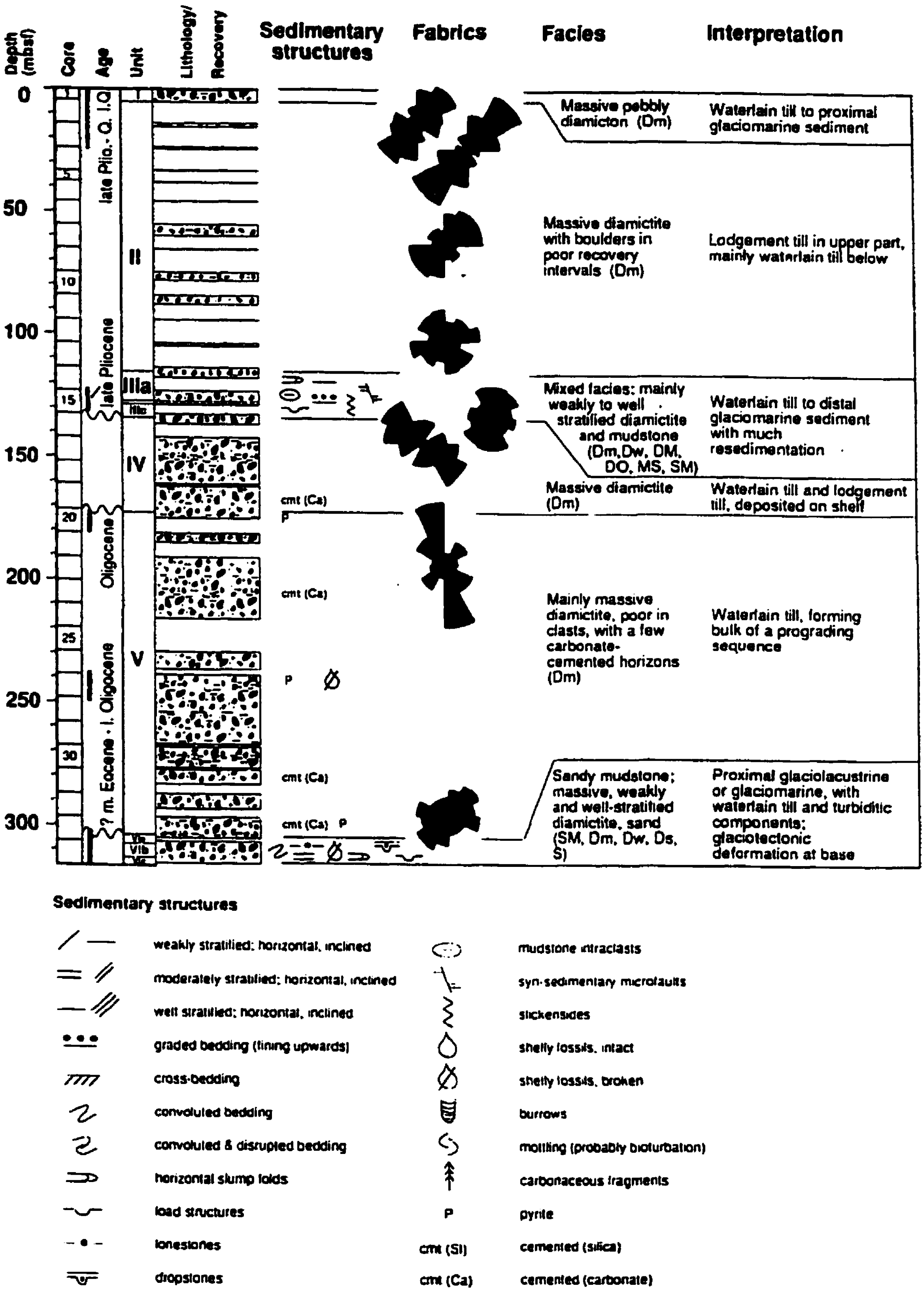


Figure 2.18. Stratigraphy, sedimentology and interpretation for (ODP Leg 119) Site 742 on the continental shelf (from Hambrey et al., 1991).

2.3.4 Multiple Locations

Anderson et al. (1983) published a substantial study that reported details of glacial and glacial marine deposits investigated during six marine geologic expeditions to the continental margin of Antarctica. Five hundred grab samples and piston sediment cores were obtained and thousands of kilometres of the seafloor was mapped. Cores were recovered from the Ross Sea, Weddell Sea, Bellingshausen Sea (Antarctic Peninsula) and along the George V coast, and seismic was acquired in the Ross Sea (Figure 1.1). Anderson et al. (1983) used this data to establish a polar glacial marine facies model. As with Orheim and Elverhøi (1981), this is an influential study of Antarctic marine geology in that it proposes that ancient glacial marine deposits should be interpreted in accordance with Antarctica's current 'polar' setting. Anderson (1999) remains a strong proponent of the notion that the present-day polar conditions of Antarctica make it a unique depositional environment and that such conditions prevailed during Pleistocene glaciations.

The 'polar' model of Anderson et al. (1983) is characterized by sediment transport confined to the basal debris zone of the glacier. Marine ice sheets ground at great depths, erode the sea floor and deposit lodgement till from the basal debris zone on the continental shelf (Figure 2.19). Ice-rafted diamictites are deposited in a narrow zone near the grounding line. Ice rafted diamictites grade seaward into muds and oozes with minor ice-rafted debris, marking the change from predominantly glacial to marine sedimentation (Figure 2.19). The modern Antarctic margin is characterized by very low sedimentation rates because sediment is trapped under ice shelves and little meltwater is released under the very cold climate conditions.

Since 1983, understanding of glacial and glacial marine depositional processes has expanded rapidly. The contrast between 'polar' and 'temperate' styles of glacial marine sedimentation is now regarded as overstated. The characteristics of the 'polar' setting, that is sediment starvation of the shelf and deposition of oozes is typical only of the present day 'interglacial'; massive sediment fluxes occurred across the shelf to the slope during earlier glaciations when ice streams moved over soft beds (Boulton and Hindmarsh, 1987; Boulton, 1996). This model is discussed at length in Chapter 3.

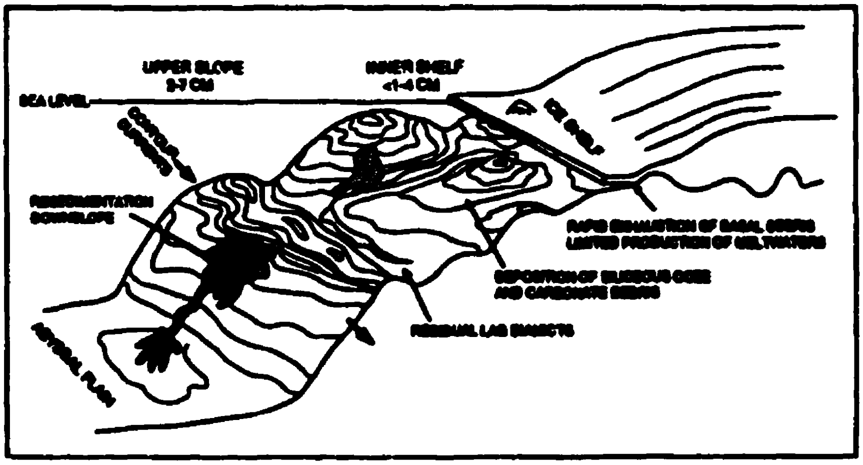


Figure 2.19. Glacial marine deposition on a 'polar' or 'sediment starved' margin. Sedimentation is restricted to minor basal debris and siliceous and organic oozes. Numbers refer to sedimentation rates (cm/1000 yr) (from Eyle and Eyles, 1992).

2.4 Phase 4 - Integrated Models: A New Approach

Recent studies have recognized the importance of integrating data from multiple existing datasets (e.g. geophysical, biostratigraphic, sedimentological) in order to construct more robust depositional models (Eyles et al., 1999, Chapter 3; Januszczak et al., in prep). Such models also enjoy the advantage of including data from studies of pre-Pleistocene glaciated basins and recent advances in understanding of northern hemisphere glaciated continental margins.

2.4.1 Antarctica

Barker et al. (1999) produced a general model of glacial sedimentation for the Antarctic margin that utilized seismic reflection profiles and data from the ANTOSTRAT (Antarctic Offshore Stratigraphy project) drilling programs. In their model, ice transport to the ice sheet margin takes place within broad, rapidly moving ice streams. Rapid ice flow is facilitated by extensive bed deformation (deformation till).

Deposition on the shelf and slope is slow during interglacials and results in mixed biogenic and terrigenous hemipelagic sediments such as diatomaceous and siliceous oozes and ice-rafted and ice-scoured diamictite. During periods of glacial advance to the shelf edge, till is transported to the outer shelf and upper slope. During glacial maxima, till deposition 'builds-out' or progrades the slope. With glacial retreat biogenic deposition resumes and till is deposited on the shelf (Figure 2.20). As with Larter and Barker (1989) and Larter and Cunningham (1993), this model promotes line source deposition of till down slope during periods of glacial maximum and fails to incorporate the observed lateral variability of the margin as shown by Bart and Anderson (1995).

The need to reevaluate much previous work from the Antarctic has recently been recognized (Fielding et al., 1997) and it has been suggested that this may be best accomplished using models derived from northern hemisphere continental margins as an analogue for Antarctic depositional processes (Clausen, 1998; Eyles et al., in press; Januszczak et al., in prep). A recent reevalution by Fielding et al. (1997) of CIROS-1 drill core from the western Ross Sea (Hambrey et al., 1989; see above) was undertaken as a training exercise for sedimentologists assigned to the Cape Roberts Project (Ross Sea-currently in progress). Hambrey et al. (1989; Section 2.3.1, Figure 2.14) interpreted all diamictite as basal till but a reassessment by Fielding et al. (1997) interpreted the diamictite facies in context with associated vertical facies and observed bedding structures and bioturbation, indicative of post-depositional reworking. These results suggest a wide range of depositional processes for diamictites previously interpreted as 'till' (Figure 2.21).

Perhaps the most complete integrated study to date is that of Domack et al. (1999) in the Ross Sea during the 1994, 1995, and 1998 austral field seasons. Diamictites were classified through integration of biostratigraphic data, textural data, geochemical and geotechnical properties, and vertical facies associations. In addition, this study was done in conjunction with a large geophysical study by Shipp et al. (1999) which provided a large seismic profile database. Together, these studies more closely resolved the nature of recent glacial geological processes in the Ross Sea. These methods and the resulting improved database should be incorporated when interpreting ancient core.

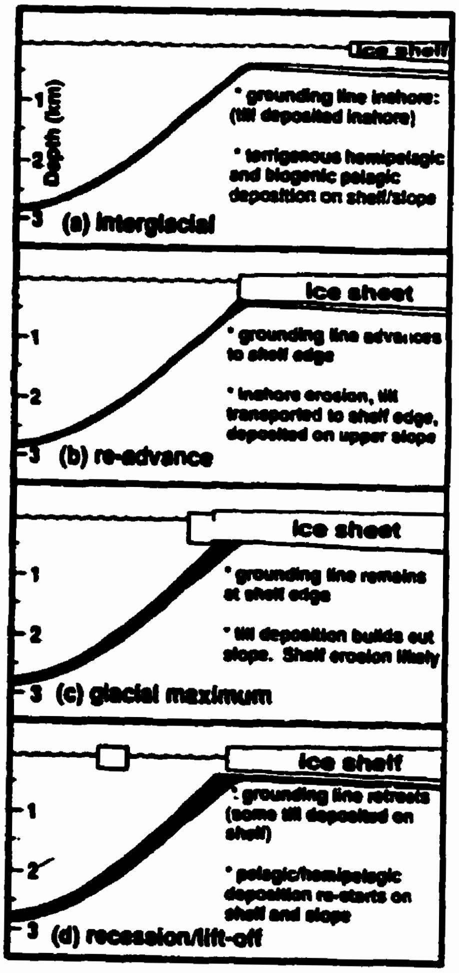


Figure 2.20. Model of deposition on the shelf and slope (modified by Barker et al., 1999, from Larter and Barker, 1989).

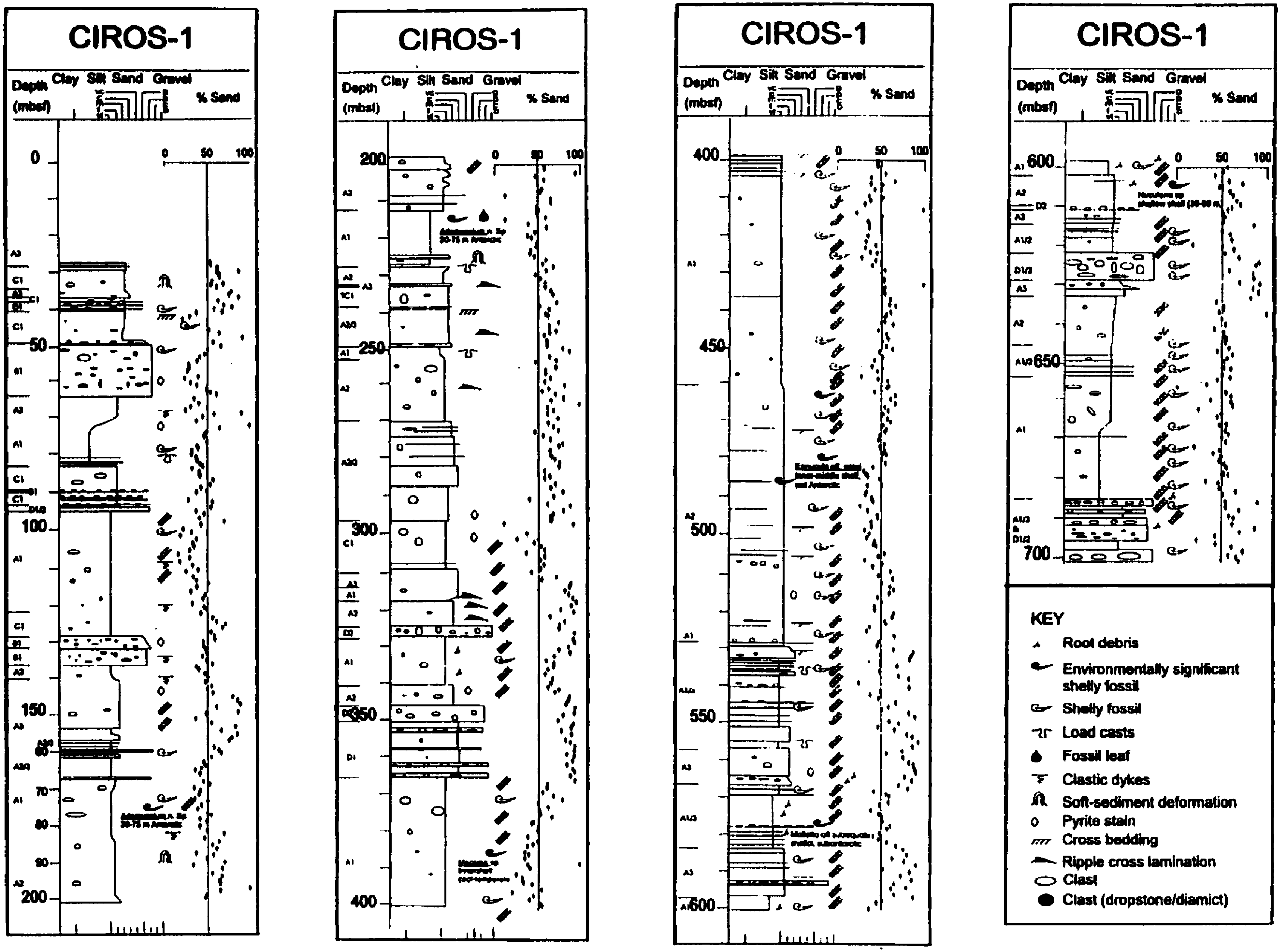

CIROS-1
Depth (mbsf)
Clay Silt Sand Gravel
% Sand
0 50 100
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
KEY
Root debris
Environmentally significant shelly fossil
Shelly fossil
Load casts
Fossil leaf
Clastic dykes
Soft-sediment deformation
Pyrite stain
Cross bedding
Ripple cross lamination
Clast
Clast (dropstone/diamict)

Figure 2.21. New graphical sedimentological log for CIROS-1 showing the vertical distribution of lithofacies (from Fielding et al., 1997).

2.4.2 Northern Hemisphere

In the accelerated exploration for oil and gas along the northwestern European continental margin, there have been great strides in understanding Pleistocene glacial depositional processes on shelves and slopes (e.g. Stoker et al., 1991). Several studies have shown that the basic structure of the Antarctic continental margin (topsets/foresets) is replicated on northern hemisphere margins implying a commonality of depositional processes and controls.

A seismic stratigraphic study of the southeast continental margin of Greenland reveal an overdeepened inner shelf and flat-lying topset beds underlain by steeply seaward-dipping foreset units (Clausen 1998; Figure 2.22). These units closely resemble those along the Antarctic continental margin (Section 2.2; Figure 1.2).

Shelf topsets are interpreted as eroded surfaces cut by grounded ice and may represent deformed basal till layers like those observed under Ice Stream B in the Ross Ice Shelf (Alley et al., 1989, Section 2.2.1). Steep well-defined foresets beds are interpreted as deformation till that has experienced subsequent downslope redeposition by debris flows. Modern scars observed in the uppermost part of the continental slope show that slumps and slides currently are involved in initial downslope transport. Discontinuous reflection facies patterns from upper paleoslopes may represent similar scars near the paleoshelf edge.

Short sediment cores and seismic profiles from the North Sea Fan (King et al., 1998) penetrated seaward-dipping glacigenic debris flows (GDFs). A strike-oriented seismic profile of the Norwegian margin reveals stacked debris flow lenses very similar to those seen on the Antarctic Peninsula (Bart and Anderson, 1995; see above) (Figure 2.23).

Sediment cores confirm that the lensoid bodies identified on seismic profiles are comprised of debris flows. Seismic continuity between shelf till and upper slope GDFs indicate a close association between glaciation at the shelf edge and GDF deposition (Figure 2.24).

Stacked debris flows are also observed by Stoker et al. (1991) with high resolution boomer profiles of the Faeroe-Shetland Channel (northwestern coast of the United Kingdom). Minor basal erosion was observed in underlying, laminated sediments and nearby boreholes revealed that the lensoid bodies observed in seismic profiles were composed of slightly overconsolidated diamictite. Aksu and Hiscott 1992 observed similar features on the eastern Canadian seaboard.

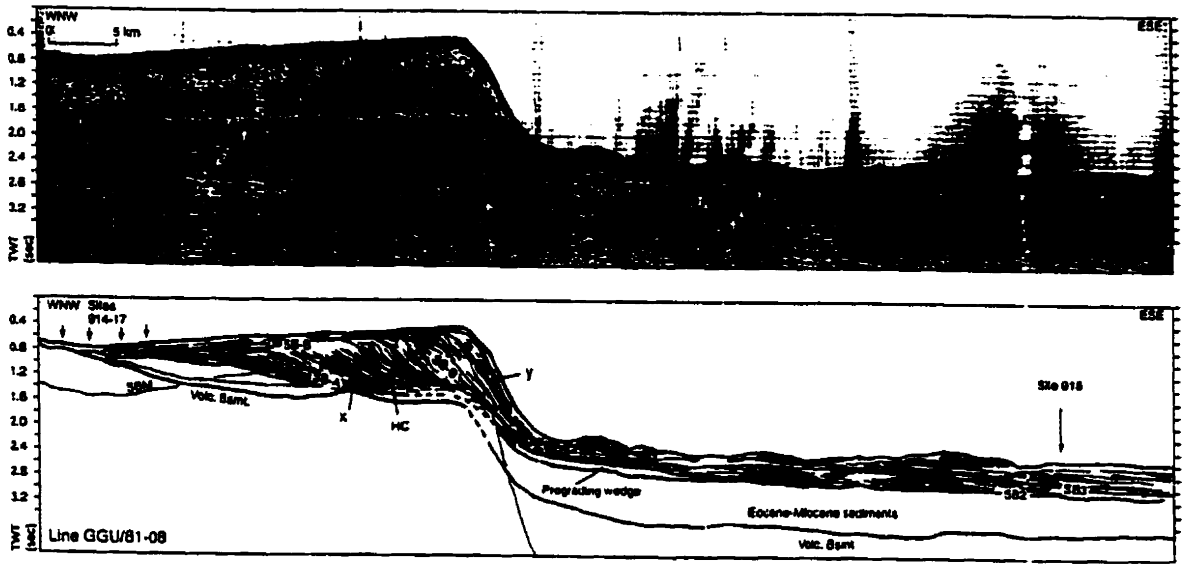


Figure 2.22. Seismic profile of the southeast Greenland glaciated continental margin (from Clausen, 1998).

Figure 2.23. Seismic strike profile of the North Sea Trough Mouth Fan. Stacked GDFs are bounded by regionally continuous reflectors marking hiatuses in GDF activity (from King et al., 1998).

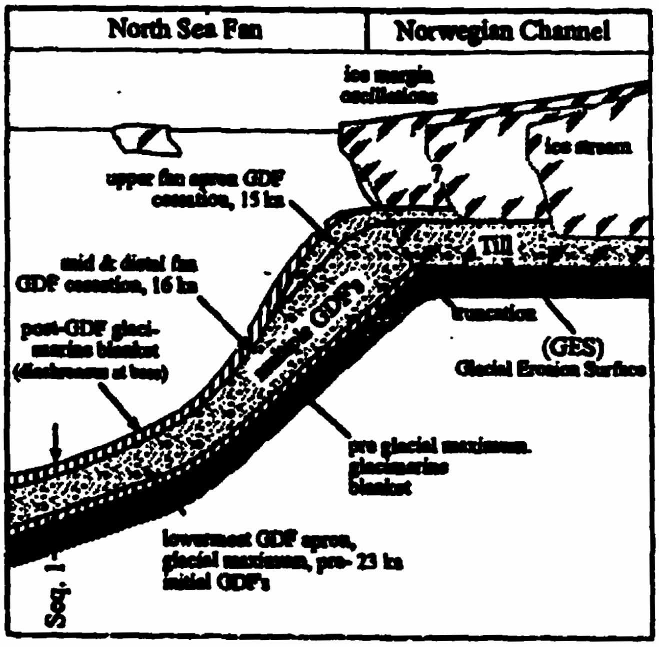


Figure 2.24. Cartoon of the development of the uppermost North Sea Trough Mouth Fan (from King et al., 1998).

2.5 Summary and Conclusions

The idea that the Antarctic represents a unique 'polar' environment is the cornerstone of much of the work that has been done in the Antarctic to date. Modern day polar conditions of 'sediment starvation' and extensive ice shelves are certainly unique but do not appear to be representative of past conditions in the Antarctic when the ice sheet expanded across the shelf. Seismic profiles of northern hemisphere glaciated continental margins show that the gross morphology and stratigraphy of the margin can be described in terms of aggrading topset units and prograding foreset units. Sedimentological work from these margins suggests that topsets are comprised of deformation till and foresets are the result of subsequent reworking of deformation till and glacial marine deposits as debris flows. In Chapter 3, this depositional model is applied to the Antarctic continental margin.

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CHAPTER 3

OCEAN DRILLING PROGRAM LEG 178 (ANTARCTIC PENINSULA): SEDIMENTOLOGY OF GLACIALLY-INFLUENCED CONTINENTAL MARGIN 'TOPSETS' AND 'FORESETS'

Abstract

The glacially-influenced Cenozoic continental margin of Antarctica shows a large-scale subsurface seismic stratigraphy consisting of uppermost flat-lying 'topsets' recording episodic aggradation of the continental shelf, that rest on seaward-dipping, wedge-shaped 'foresets' formed by the progradation of the continental slope. Seismo-stratigraphic profiles and previous Ocean Drilling Program (ODP) drillcore data (Leg 119) suggest that topsets and foresets are composed predominantly of acoustically-transparent diamictite facies but origin is poorly-constrained. Ocean Drilling Program Leg 178 (February-April 1998) drilled two sites (1097, 1103) through the outer Antarctic Peninsula Pacific continental shelf into strata no older than late Miocene or early Pliocene (< 4.6 Ma). Recovery at shallow depths in loosely-consolidated, iceberg-turbated bouldery sediments was poor but improved with increasing depth and consolidation to allow detailed description of litho- and biofacies and interpretation of depositional environment. Site 1097 lies on the outer shelf within Marguerite Trough, which is a major outlet for ice expanding seaward from the Antarctic Peninsula, and reached a maximum depth drilled of 420 m below the sea floor (mbsf). Strata consist of thick intervals of massive diamictite containing reworked and abraded marine microfauna. These facies are interpreted as tills produced by subglacial re-working of marine sediments (deformation till). Tills are separated by intervals of stratified and graded diamictites that contain an *in situ* marine biofacies characteristic of a proglacial marine setting. Other intervals consist of bioturbated mudstones with dropstones and contain a diverse in situ fauna recording deposition on an open shelf close to the glacial margin. The sedimentary record at Site 1097 is consistent with aggradation of a 'topset' by till deposition alternating with glacial-marine sedimentation. Site 1103 reached a depth of 363 mbsf through massive and chaotically-stratified diamictites with abundant silt rip-up clasts interbedded with massive and weakly-graded sandstones and mudstones that are no older than Late Miocene. This succession appears to record sediment gravity flow on an active slope close to a source of poorly-sorted glacial debris. The sedimentary record and seismic stratigraphy at site 1103 is consistent with deposition on a continental slope 'foreset' by debris flows and turbidity currents.

3.0 Introduction

Areally-extensive erosion of continental surfaces by ice sheets releases large fluxes of sediment to marine basins resulting in accelerated growth of continental shelves and slopes (Piper et al., 1990; Boulton, 1990; Syvitski, 1991; Eyles et al., 1991; Gipp, 1993; Bart and Anderson, 1995; Clausen, 1998; Solheim et al., 1998; Steckler et al., 1999). In Antarctica, the Antarctic Peninsula Pacific continental margin (APPcm) has experienced very rapid Late Cenozoic growth in response to repeated advances of the Antarctic Ice Sheet to the shelf edge (Larter and Barker, 1989; Larter and Cunningham, 1993; Bart and Anderson, 1995; Barker et al., 1999; Anderson, 1999). In broad terms, the stratal geometry of strata underlying the Peninsula continental margin consists of large-scale 'topset' strata, recording aggradation of the shelf, and underlying clinoform 'foreset' strata recording progradation of the continental slope (Vanneste et al., 1994; Bart and Anderson, 1995; Vanneste and Larter, 1995). This structure closely resembles that identified elsewhere around Antarctica (e.g., Bart and Anderson, 1995; Vanneste and Larter, 1995; Nitsche et al., 1995; ten Brink et al., 1995; Larter et al., 1995; De Santis et al., 1995; Brancolini et al., 1995) and on other glaciated margins in the northern hemisphere (Larsen et al., 1994; Clausen, 1998). Water depths across the Antarctic shelf are generally greater than that of mid- and low-latitude shelves suggesting continued subsidence of the Antarctic margin since the onset of Cenozoic glaciation (Hambrey et al., 1991; Elliot, 1985). This has promoted accommodation of very thick glacially-influenced topset/foreset successions around the Antarctic margin (Cooper et al., 1995).

There have been several attempts to understand the evolution of topset and foreset strata developed on mid-latitude glaciated continental margins by modeling the interplay of tectonics, glacio-isostatic and eustatic sea level variation and sediment supply (e.g., Boulton, 1990; Gipp, 1993; ten Brink et al., 1995; Steckler et al., 1999). Such models are based on substantial seismic, age and sedimentary databases. In contrast, understanding and modeling of the evolution of the Antarctic continental margin is constrained, despite considerable seismic data, by a lack of subsurface stratigraphic and age data and limited knowledge of depositional processes (see discussions in ten Brink et al., 1995; Bart and Anderson, 1995). Better geological sampling of the Antarctic margin is needed and this is the principal objective of the Antarctic Offshore Stratigraphy project (ANTOSTRAT) centred around the efforts of the Ocean Drilling Program and the Cape Roberts (Ross Sea) drilling program (see Barker and Cooper, 1998). The purpose of this paper is to present detailed lithofacies and biofacies data from the APPcm that helps constrain the nature of depositional processes involved in growth of the continental margin.

3.0.1 Study Area: Antarctic Peninsula Pacific Continental Margin (APPcm)

Topsets and foresets are well developed along the APPcm (Figures 3.1, 3.2). A dominant seismo-stratigraphic component of topsets and foresets are acoustically-chaotic and transparent seismo-facies that are interpreted as poorly-sorted diamictites deposited under or at the margin of an ice sheet extending to the shelf edge (e.g., Pope and Anderson, 1992; Bart and Anderson, 1995). However, information regarding the sedimentology and origin of these poorly-sorted facies along the APPcm is limited to short (<5 m) piston cores (Pope and Anderson, 1992;

Pudsey et al., 1994). In early 1998, Leg 178 of the Ocean Drilling Program drilled nine sites across the APPcm from the continental rise to the mid-shelf (Figure 3.1) with the purpose of collecting sedimentological data regarding diamictites and identifying aggradational and progradational processes leading to the development of topsets and foresets. This paper presents detailed descriptions of diamictites and associated biofacies recovered by ODP Leg 178 drilling on the continental shelf and then discusses the implications of such data for understanding the evolution of the APPcm.

3.1 Ocean Drilling Program Leg 178

ODP Leg 178 collected a total of 1806 m of core from nine drill sites along the APPcm (Figure 3.1). One of the objectives of Leg 178 was to identify and compare sedimentary records preserved in shelf topsets (i.e. paleoshelf strata), in slope foresets (i.e. paleoslope strata) and in hemipelagic sediment 'drifts' on the continental rise. Three sites (1095, 1096 and 1101) were drilled in deep water (3 - 4 km) on the continental rise where sedimentation has been dominated by distal fine-grained turbidity currents sourced from the adjacent continental slope (Rebesco et al., 1996). These sites record glacial/interglacial cyclicity back to 9 Ma, details of which are being reported elsewhere (Barker et al., 1999). Shelf sites (1097, 1100, 1102, 1103; Figure 3.1) were drilled in water depths between 400 and 500 m. Drilling was slow and difficult because of interruptions by icebergs that drifted across the drill sites, by limitations on drilling imposed by ship heave in heavy swells, and by the coarse bouldery nature of sediments immediately underlying the iceberg-scoured sea floor.

This paper focuses on data derived from shelf sites 1097 and 1103 (Figure 3.1). At both sites, cores were described using formal descriptive schemes (e.g., Eyles et al., 1983). In addition, matrix fines from representative facies were systematically processed for marine microfossils (Shipboard Scientific Party, 1999a; Shipboard Scientific Party, 1999b). Overall core recovery was poor but in most cases sediment samples were retained by the core catcher allowing biofacies sampling. As a result, biofacies data allow a more complete and thorough interpretation of paleoenvironments recorded at each site (see below).

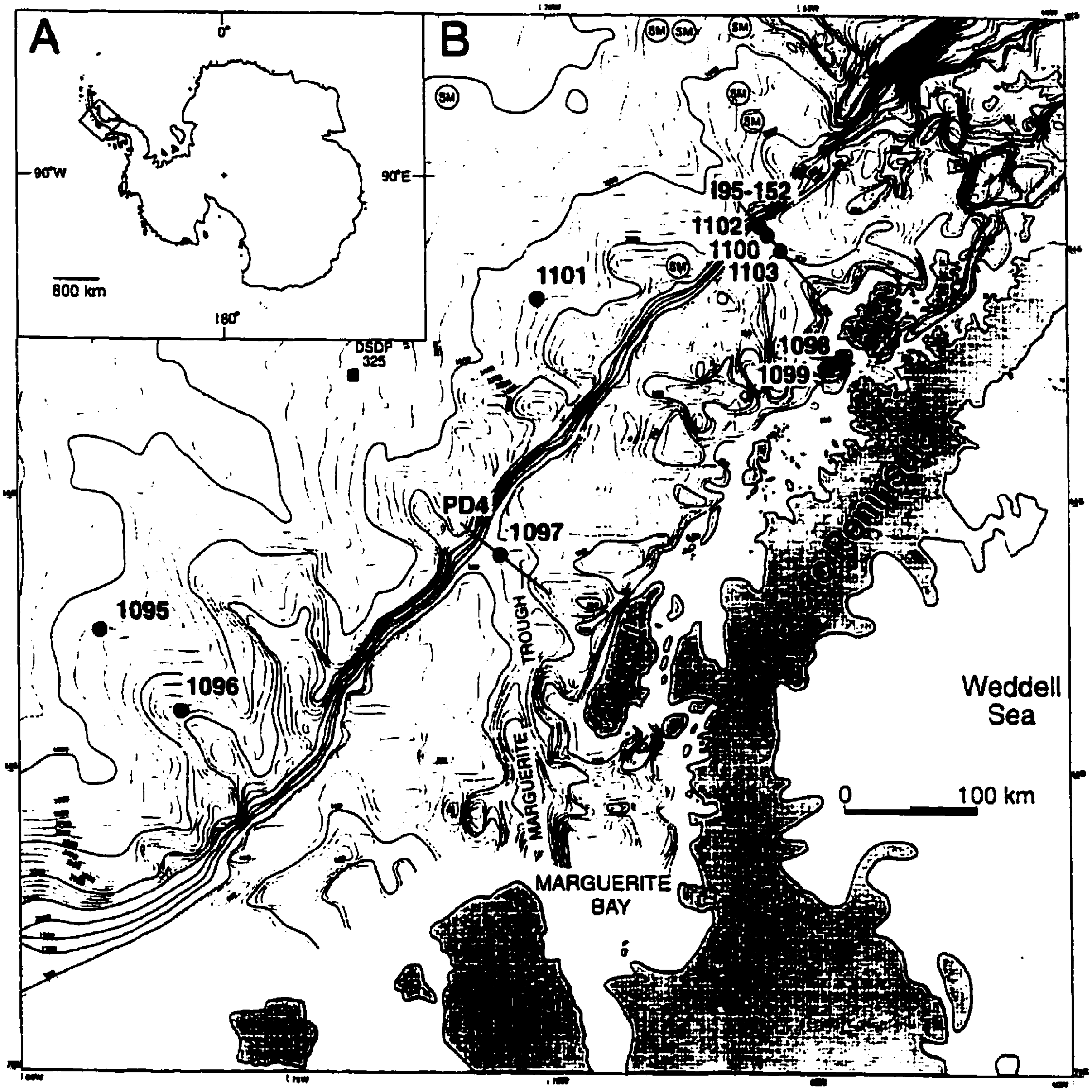


Figure 3.1. Location of ODP Leg 178 drill sites along the Antarctic Peninsula Pacific margin. This paper describes core recovered at sites 1097 and 1103 (Rebesco et al, 1998; Barker et al., 1999;). Location of seismic lines PD4 (Fig. 2A) and 195-152 (Fig. 2B) are also shown.

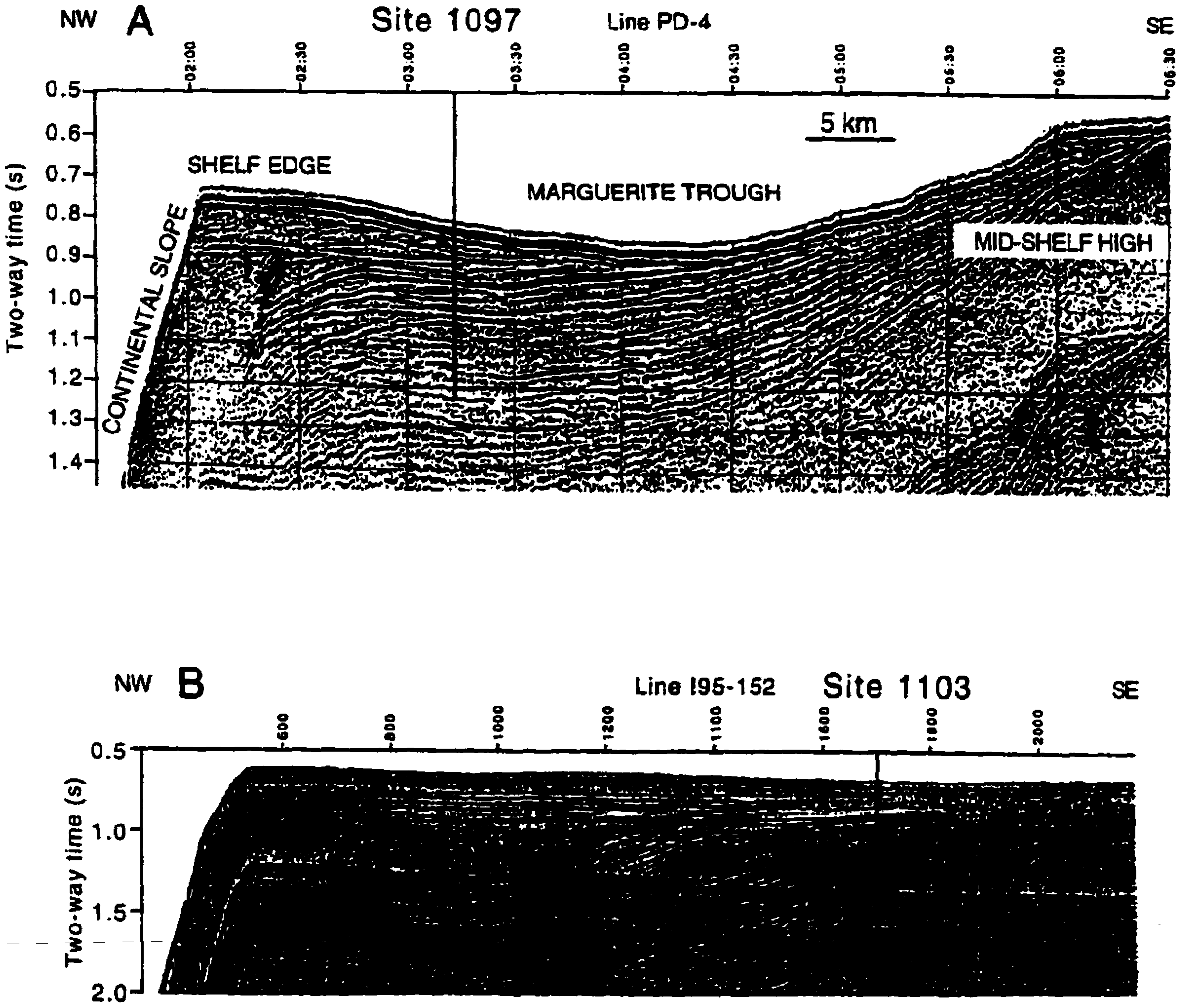


Figure 3.2. Acoustic stratigraphy at Leg 178 Sites 1097 and 1103 showing flat-lying topsets recording aggradation of the shelf, and steeply-dipping foresets recording slope progradation; reproduced from Bart and Anderson (1995) and Barker et al. (1998). See Figure 1 for location of profiles.

3. 2 Site 1097

Site 1097 is located on the outer continental shelf in 552 m water depth, and some 14 km from the shelf edge (Figure 3.1). The site lies within Marguerite Trough which is occupied episodically by grounded ice moving out of Marguerite Bay to the shelf edge. Acoustic stratigraphic profiles oriented perpendicular to the shelf edge show a relatively simple wedge-shaped succession of topset/foreset reflectors that dip seawards from a structural mid-shelf high some 30 km landward of Site 1097 (Figure 3.2A). This, however, is a simplistic picture of the three-dimensional geometry of strata below the continental margin. Seismic data collected parallel to the shelf edge by Bart and Anderson (1995) identify a more complex stratal geometry identified by stacked, commonly amalgamated unconformities showing broad channels and chaotic, transparent acoustic facies they interpreted as till. Rotary drilling at Site 1097 reached a depth of 436.6 metres below the sea floor (mbsf) using rotary-core-barrel (RCB) method; recovery was very poor in the upper 80 m but some 57 metres of core was recovered from the lower part of the hole (14% recovery) (Figure 3.3A).

Age constraints at Site 1097 are provided by diverse assemblages of diatoms typical of the *Fragilariopsis barroni* and upper part of *Thalassiosira imura* Zones. Radiolarian assemblages include species typical of shelves (e.g., *Spongotrochus glacialis*, *Spongopyle osculosa* and *Porodiscid spp.*,) with species consistent with an age in the Upsilon Zone (e.g., *Helotholus vema*, *Prunopyle titan*, *Lampromitra coronata*) (Osterman et al., in prep.; Shipboard Scientific Party, 1999a). These data suggest ages greater than 4.85 Ma below 218 mbsf and younger than 5.6 Ma below 289 mbsf. Age dating of the upper part of the succession is not possible because of the predominance of diamictite facies that are barren or contain reworked microfossils. From the biofacies data it can be concluded that recovered strata are no older than Early Pliocene at Site 1097 (Figure 3.3A). What follows is a description of the principle lithofacies and biofacies recovered and an interpretation of depositional conditions at Site 1097.

3.2.1 Lithofacies

Massive diamictite (Dmm)

The term diamictite refers to poorly-sorted lithified admixtures of clasts (defined as larger than sand sized) supported by matrix fines. Massive, matrix-supported diamictite (facies Dmm; Figures 3.3, 3.4, 3.5A) represents the most common facies identified at Site 1097 comprising some 65% of the total cumulative length of core recovered. The maximum recovered interval through such facies is 3 m (Core 37; Figures 3.3, 3.4A). Matrix grain-size is highly variable and varies from silty mud (10%-20% sand, 50%-75% silt, and 10%-40% clay) to sandy silty-clay (up to 30% sand) with clast contents varying from clast-rich (> 20% gravel) to poor (10%-20%). The largest boulder drilled was at least 50 cm in diameter but the frequent occurrence in some poorly-recovered intervals of freshly-fractured pieces of the same lithology also denotes the presence of large boulders. Clast lithologies include volcanic (basalt, volcaniclastics, andesite, and rhyolite) and plutonic igneous rocks (mafic, granite, and diorite) all derived from local Antarctic Peninsula sources (e.g., Pope and Anderson, 1992; Elliot, 1995). The mineralogy of the sand and silt fraction is dominantly quartz (30%-80%) and feldspar (5%-20%) with minor lithic fragments, mica and hornblende. Trace amounts of tephra occur (core 13) and manganese micronodules are also present (cores 10 and 12). Matrix color varies from dark gray (5Y 3/1) to green (5GY 3/1). With a single exception (Core 44; see below), massive diamictite facies at Site 1097 contain reworked and abraded diatoms, foraminifers, and sponge spicules (see below). In Core 44, massive diamictite with moderately well-preserved marine microfossils and borrows, is transitional to bioturbated sandy mud with dropstones (Figure 3.4B).

Graded and stratified diamictite (Dmg, Dms)

These facies show an internal structure created by size-sorting of clasts and account for 10% (about 5 m) of recovered sediments at Site 1097. Beds are between 20 and 50 cm thick (Figure 3.4). Graded diamictite facies (facies Dmg; Figures 3.4, 3.5B) show either an upward decrease in clast size (normal grading) or upward increase (inverse grading). Core 27 shows a normally-graded diamictite bed up to 40 cm thick capped by burrowed muds containing dropstones, well-preserved sponge spicules and *in situ* marine microfossils (Figure 3.4A). An overlying inverse-to-normal graded diamictite bed rests with a sharp erosive contact on underlying muds and contains a rip-up clast of altered tephra (Figure 3.4A).

Stratified diamictite facies (facies Dms; Figure 3.4) are defined by slight and non-systematic variations in matrix texture and clast contents giving rise to a crude bedding (e.g., Core 25; Figure 3.4A). These facies are interbedded with thin mud beds (< 10 cm) that contain *in situ* marine microfauna and flora.

Mudstone (Fm, Fl)

Mudstone facies account for 25% of recovered sediment at Site 1097. These facies are either massive or weakly laminated (Figure 3.5C) and range in texture from silty-clay (e.g., Core 36; 10% sand, 40%-50% silt, and 30-50% clay) to a clayey-silt (e.g., core 34; 5% sand, 25%-69% silt and 30%-75% clay; Figure 3.4A; Shipboard Scientific Party, 1999a). Mudstones contain dropstones and shell fragments, and are bioturbated. In cores 34 to 36, the content of gravel-sized ice-rafted clasts in several thin intervals is sufficiently high (<10%) to warrant description as diamictite (Figures 3.4A, 3.5D).

3.2.2 Biofacies and interpretation of lithofacies at Site 1097

At Site 1097, radiolarians, diatoms and foraminifers are all present, with relative abundance and degree of preservation varying from sample to sample (Shipboard Scientific Party, 1999a). Three qualitative biofacies (A,B,C) can be defined for benthic foraminiferas in 38 samples at Site 1097 and these assist in identification of depositional environment for lithofacies described in core.

Biofacies A (subglacially-reworked sediment)

Biofacies A consists of poorly preserved, reworked assemblages of benthic foraminifers. Typical samples contain less than 12 robust foraminifer specimens (typically the benthic foraminifers *Globocassidulina subglobosa* and *Cassidulinoides parkerianus*) which are commonly yellow-colored, broken or filled with sediment indicating post-mortem transport

(Figure 3.6). Worn, dark brown and grey colored fragments of biogenic matter such as *Inoceramus* (Bivalvia) prisms, mollusc shell fragments and echinoderm spines are common.

Biofacies A is typical of massive diamictite facies at Site 1097 (Figure 3.4). The absence of well-preserved *in situ* microfossils, any internal stratification or bioturbation in such diamictites precludes a glaciomarine origin by the deposition of suspended sediment and ice-rafted debris. A debris flow (debrite) origin is possible but diamictites are unstructured and do not show chaotic bedding or the flow banding seen in debrites (e.g. Visser, 1983) and seen at Site 1103 (see below). Given their overall thickness (Figure 3.3A) and the ubiquitous presence of reworked and abraded marine microfossils (Figure 3.3B) massive diamictites at Site 1097 are most logically interpreted as till. The ubiquitous occurrence of broken shells and mixed and abraded microfossils is strong evidence of subglacial abrasion and mixing. In this regard, diamictites are likely to have been deposited as 'deformation' till where marine sediment has been reworked subglacially and retransported. Subglacial transport of pre-existing marine sediment has been widely invoked in explaining massive diamictite with reworked marine microfossils on glaciated continental surfaces and shelves (e.g., Osterman, 1984; Boulton, 1990; ten Brink et al., 1995; Boulton 1996; Clark et al., 1996; Licht et al, 1999; Shipp et al., 1999; see Discussion).

Biofacies B (ice-contact glaciomarine sediment)

Biofacies B contains moderately preserved and more abundant and diverse assemblages of foraminifers. The dominant benthic foraminifers (*Globocassidulina subglobosa* and *Cassidulinoides parkerianus*) are the same as in Biofacies A but the difference is their better preservation in B. Biofacies B occurs in stratified and graded diamictites that are interbedded with bioturbated mudstones (Figure 3.4) and is typical of ice-proximal glaciomarine depositional settings characterised by low salinity and high sedimentation rates (Shipboard Scientific Party, 1999a). Graded diamictite facies (facies Dmg; Figure 3.4) are indicative of turbulent downslope flow resulting in the sorting of different size fractions (e.g., Walker, 1992). Correspondingly, stratified and graded diamictite (facies Dms, Dmg) containing Biofacies B are interpreted as subaqueous sediment gravity flows. Interbeds of mudstone (e.g., core 25; Figure 3.4A) probably record pauses between debris flows allowing accumulation of suspended sediment. An ice-proximal glaciomarine depositional setting is indicated, most likely where subglacial debris such as till was released and moved downslope by mass flow (Figure 3.3B).

Biofacies C (ice-distal glaciomarine sediment)

This biofacies is distinctly different from both Biofacies A or B because it is characterised by large numbers (up to 1000 specimens) of well-preserved foraminifera species in association with well-preserved biogenic material. Species are dominated by *Globocassidulina subglobosa*, *Cassidulinoides parkeriamus*, *Astrononion echolsi*, *Epistominella vitrea* and *Fursenkoina pauciloculata* (Figure 3.6) typical of the present day outer Antarctic shelf where water depths are no greater than 500 m (Osterman et al., in prep); a similar biofacies is reported by Ishman and Webb (1988). At Site 1097, Biofacies C occurs in massive diamictites (cores 35, 36 and 44) that are transitional to bioturbated muddy sands with ice-rafted clasts (facies Fmd; Figures 3.4A, 3.4B). Indistinct trace fossils such as burrows with poorly-defined walls are also present and likely indicate soft sediment at the time of burrowing. Because of these characteristics, massive diamictites containing Biofacies C are interpreted as glaciomarine in origin produced largely as 'rain-out' facies produced by suspension settling of mud with coarser material deposited by floating ice (Figure 3.3B). Variation in the flux of IRD through time gives rise to transitions from mud with sufficient numbers of clasts to be identified as diamictite (facies Dmm), to mudstone with isolated ice-rafted clasts (facies Fmd; Figure 3.4).

Weakly-bioturbated, massive and laminated muds with high IRD content suggest influxes of meltwater, suspended sediment and icebergs to Site 1097 during early Pliocene (?) time (Shipboard Scientific Party, 1999a). Such deposition suggests a subpolar or temperate glacier regime and the transport of fine sediment as suspended mud plumes derived from subglacial meltwaters. Notably, the biogenic component of the mud within these glaciomarine intervals is generally less than 10% (Shipboard Scientific Party, 1999a) which is much less than the biogenic component of modern sediments accumulating on the present day Antarctic Peninsula shelf. For example, many of the cores described by Pope and Anderson (1992) are capped with diatomaceous muds; the upper part of cores analyzed by Pudsey et al. (1994) contain 30-60% diatoms. The low values recorded in muds at Site 1097 could reflect climatic factors such as more temperate conditions and an influx of fine-grained meltwater-derived terrigenous sediment input or other environmental factors such as reduced salinity around an ice margin terminating on the shelf.

3.2.3 Depositional setting and environmental interpretation of Site 1097

Site 1097 is dominated by thick, massive diamictite facies containing Biofacies A and confidently interpreted as till. Despite the poor recovery in the upper part of the hole, biofacies recovered from core catchers are exclusively of type A, characterised by abraded and reworked foraminifer species, which is diagnostic of till. In combination with seismic reflection data that show flat-lying reflectors in the area of Site 1097, it is suggested that the stratigraphy at this site was deposited in a shelf setting. The succession penetrated at Site 1097 is consistent with repeated subglacial aggradation of till (S; Figure 3.3A) and glaciomarine sediment (G; Figure 3.3A) on a shelf 'topset' during successive glacial/interglacial cycles. It may be significant that stratigraphic intervals identified by lithofacies and biofacies as till recording subglacial conditions (S; Figure 3.3A), increase in thickness upwards at Site 1097. This trend may reflect decreased bypassing of the shelf as the width of the shelf increases through time and less glacial sediment is swept across the shelf by glaciers and 'lost' downslope. Alternatively, the upward increase in thickness of subglacial deposits can be simply interpreted as indicating longer duration glaciations as suggested by Bart and Anderson (1995) (see Discussion).

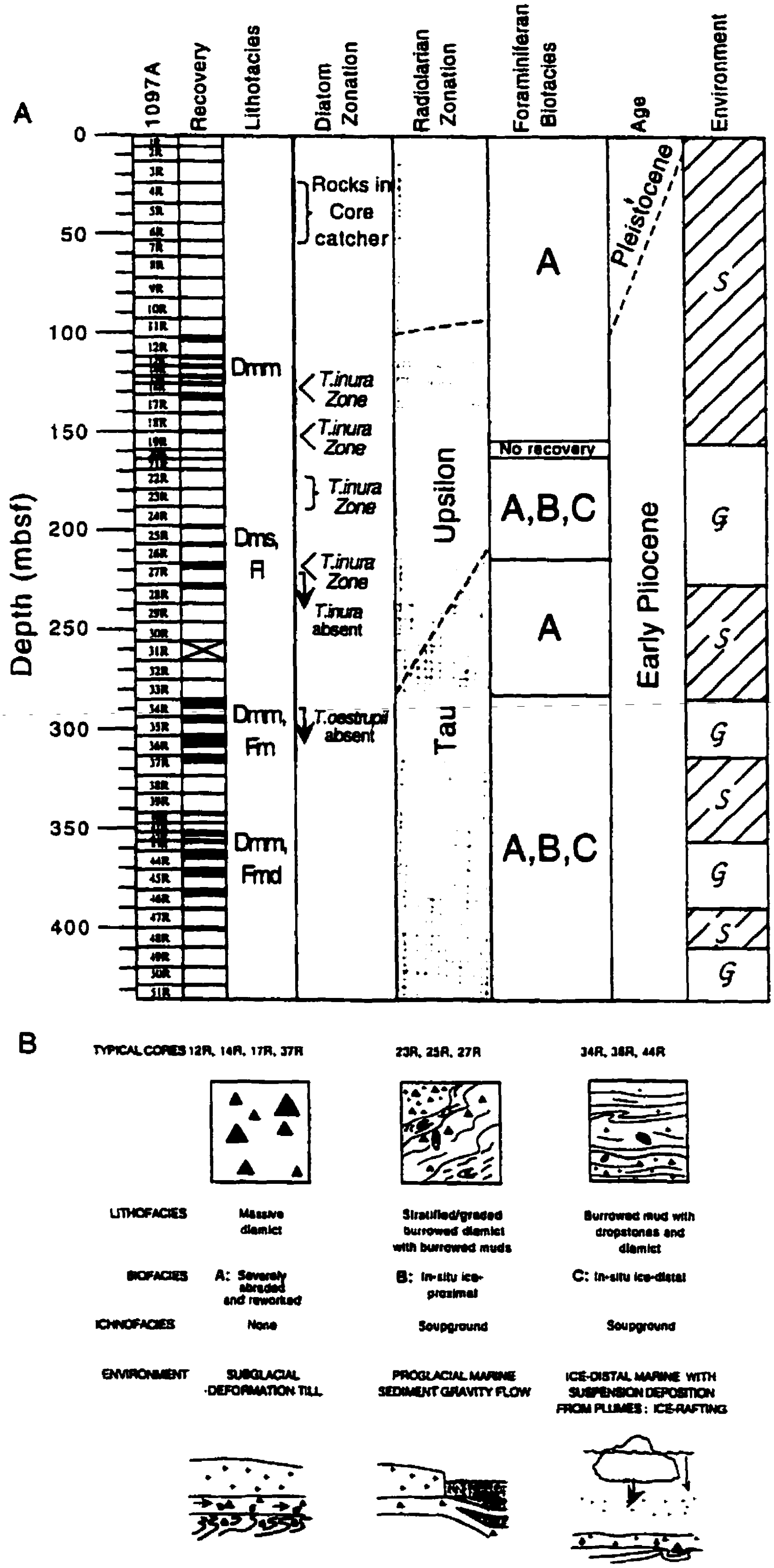
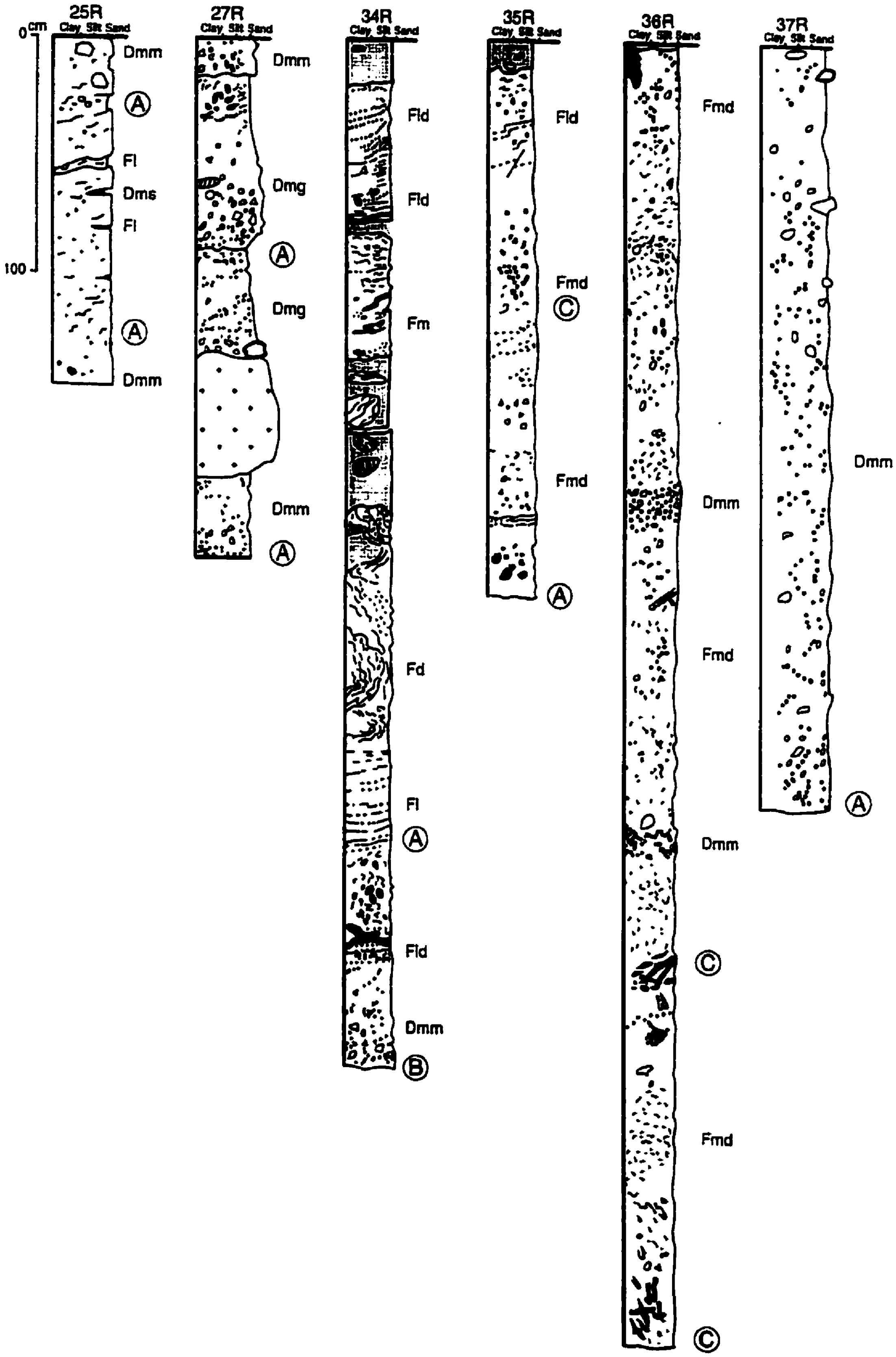

A
1097A
Recovery
Lithofacies
Diatom Zonation
Radiolarian Zonation
Foraminiferan Biofacies
Age
Environment
Depth (mbsf)
0
50
100
150
200
250
300
350
400
Dmm
Dms, Fl
Dmm, Fm
Dmm, Fmd
Rocks in Core catcher
T.inura Zone
T.inura Zone
T.inura Zone
T.inura Zone
T.inura absent
T.oestrupii absent
Upsilon
Tau
A
No recovery
A,B,C
A
A,B,C
Pleistocene
Early Pliocene
S
G
S
G
S
G
S
G
B
TYPICAL CORES 12R, 14R, 17R, 37R
23R, 25R, 27R
34R, 38R, 44R
LITHOFACIES
Massive diamict
Stratified/graded burrowed diamict with burrowed muds
Burrowed mud with dropstones and diamict
BIOFACIES
A: Severely abraded and reworked
B: In-situ ice-proximal
C: In-situ ice-distal
ICHNOFACIES
None
Soupground
Soupground
ENVIRONMENT
SUBGLACIAL DEFORMATION TILL
PROGLACIAL MARINE SEDIMENT GRAVITY FLOW
ICE-DISTAL MARINE WITH SUSPENSION DEPOSITION FROM PLUMES : ICE-RAFTING

Figure 3.3 A. Summary figure for Site 1097 showing core recovery and generalized lithofacies. Biostratigraphic age control is provided by diatoms (specific sample locations marked) and radiolarian (stippling indicates barren intervals). Benthic foraminifer analysis identifies two intervals containing only rare foraminifers (Biofacies A) and two intervals containing mixed biofacies (A, B and C) (see text for definition of the biofacies). Inferred depositional environment (S: subglacial, G: glaciomarine); interpretation of environment where lithofacies were not recovered is based on biofacies assemblages present in core catcher. Note the increasing thickness of subglacially deposited facies upwards. B. Environmental interpretation of lithofacies and associated biofacies recovered from Site 1097.


0 cm
100
25R
Clay Silt Sand
Dmm
Ⓐ
Fl
Dms
Fl
Ⓐ
Dmm
27R
Clay Silt Sand
Dmm
Dmg
Ⓐ
Dmg
Dmm
Ⓐ
34R
Clay Silt Sand
Fld
Fld
Fm
Fd
Fl
Ⓐ
Fld
Dmm
Ⓑ
35R
Clay Silt Sand
Fld
Fmd
Ⓒ
Fmd
Ⓐ
36R
Clay Silt Sand
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Dmm
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Dmm
Ⓒ
Fmd
Ⓒ
37R
Clay Silt Sand
Dmm
Ⓐ

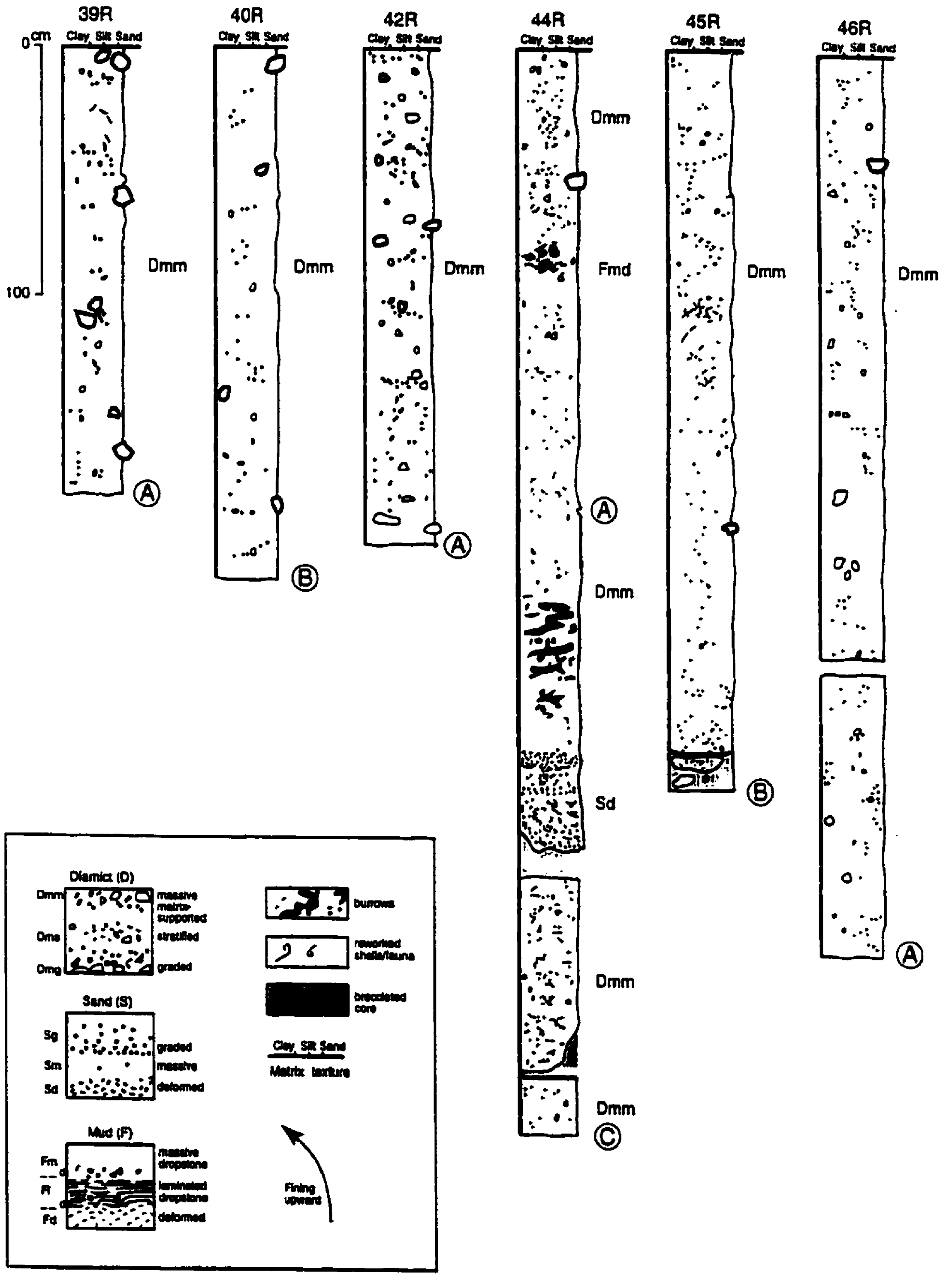

Figure 3.4 A, B. Graphic logs from representative cores at Site 1097 showing location of benthic foraminifer biofacies A, B and C.

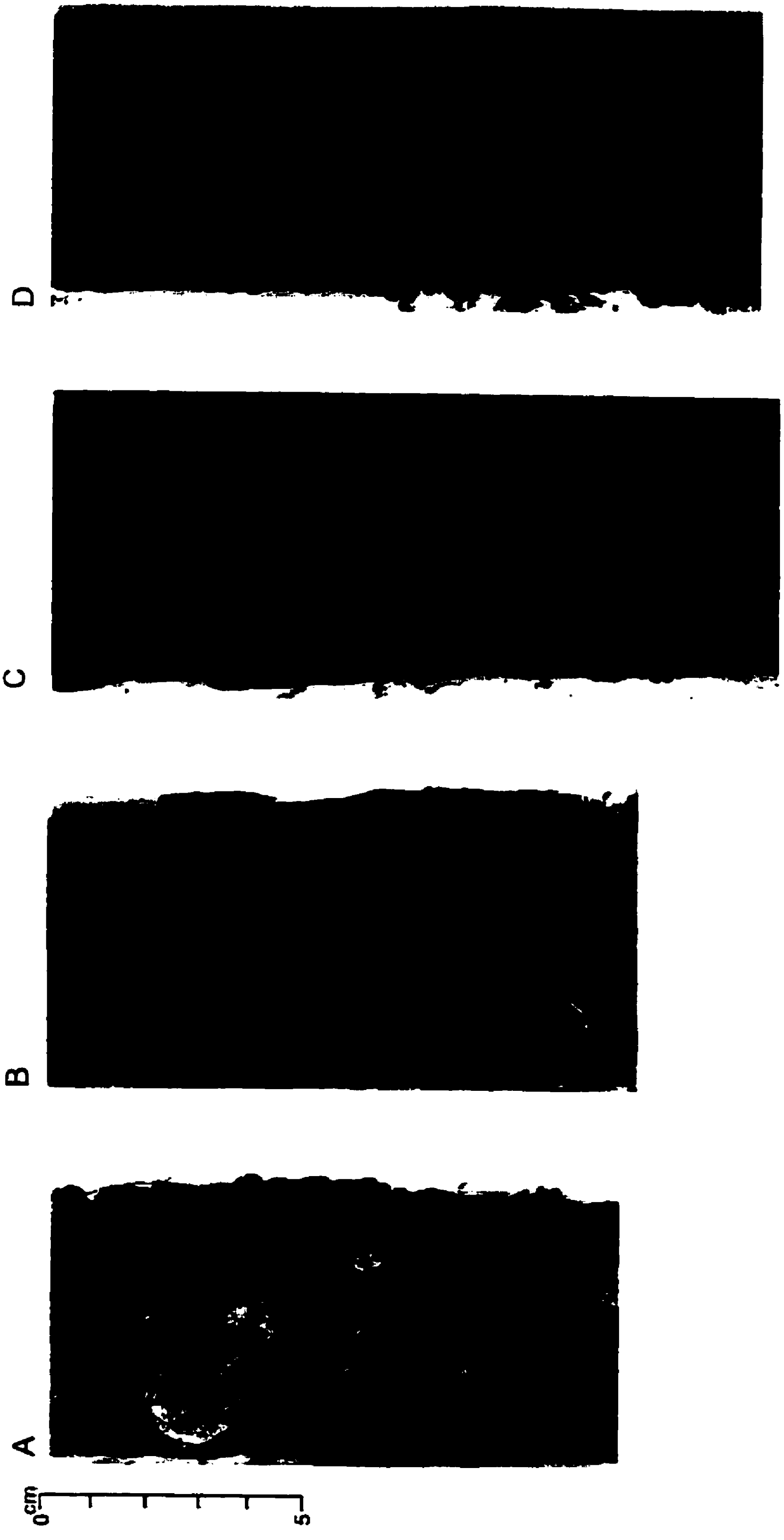
D
C
B
A
0 cm
5

Figure 3.5. Lithofacies from Site 1097.

A; Massive diamictite (facies Dmm): Site 1097A Core 10R Section 1 interval 38-49 cm.

B; Graded diamictite (facies Dmg) showing overlying laminated marine mudstones (see Fig. 4A for graphic log): Site 1097A Core 27R Section 1 interval 108-120 cm.

C; Weakly-laminated, bioturbated marine mudstones separating graded diamictite beds (see Fig. 4B): Site1097A Core 27R Section 1 interval 87-102 cm.

D; Weakly-laminated mudstone with ice-rafted clasts. This facies is transitional to diamictite (Fig. 4A): Site 1097A Core 34R Section 1 interval 26-40 cm.

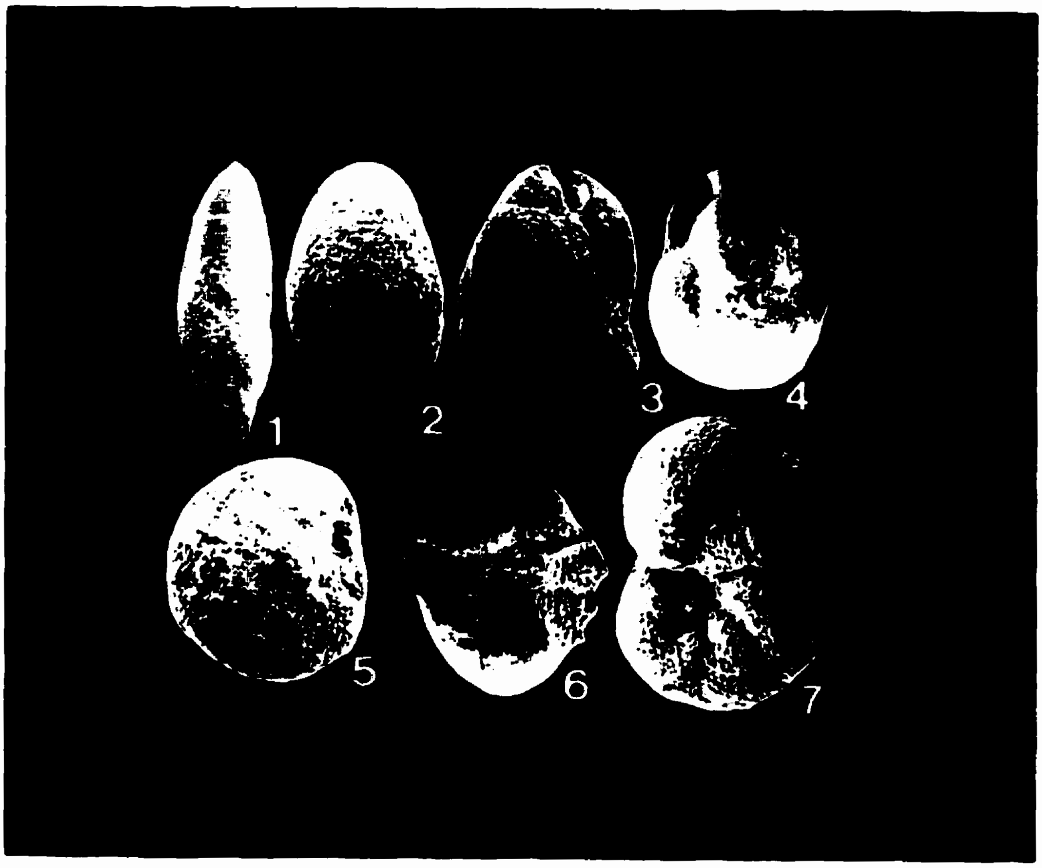

Figure 3.6. Most common benthic foraminifera of Site 1097

Fursenkoina pauciloculata (Brady), 136x, 1097A-35R-1W, 100-102 cm

Nonionella auricula (Heron-Allen and Earland), 153x, 1097A-35R-1W, 100-102 cm

Cassidulinoides parkerianus (Brady), 153x, 1097A-35R-1W, 100-102 cm

Globocassidulina subglobosa (Brady), 102x, 1097A-35R-1W, 100-102 cm

Epistominella vitrea (Parker), 221x, 1097A-35R-1W, 100-102 cm

Ehrenbergina glabra (Heron-Allen and Earland), 101x, 1097A-35R-1W, 100-102 cm

Nonionella iridea (Heron-Allen and Earland), 169x, 1097A-35R-1W, 100-102 cm

3.3 Site 1103

Site 1103 was drilled in 493 m of water northwest of Anvers Island (Figures 3.1, 3.2). The total depth of the hole was 355.39 mbsf (Figure 3.7). Recovery from the upper 247 m was minimal (2.3%) but improved in the lower 115 m where 36.3 m of sediment was recovered (34% recovery). Seismic reflectors are flat-lying in the upper part of the hole but show an increasing seaward dip toward the base of the hole (Figure 3.2).

3.3.1 Lithofacies

Three dominant lithofacies can be identified at Site 1103 (Figures 3.8, 3.9). These are massive and chaotically-stratified diamictites (50% of recovered core), sandstone (25% of recovered core) and mudstones (25% of recovered core) (Shipboard Scientific Party, 1999b).

Diamictite (Dmm, Dms)

Diamictite facies are massive or chaotically-stratified. Thick-bedded (20 cm to 4.2 m) massive, unstructured and matrix-supported facies (facies Dmm; Figures 3.8, 3.9A, B) alternate with medium- to thin-bedded (< 30 cm) chaotically-stratified facies (facies Dms; Figures 3.8, 3.9C, D) showing a distinct 'flow-banding' (Visser, 1993) defined by stringers and streaks of deformed mudstone (Figure 3.10). Diamictites vary from clast-rich (> 20% gravel) to clast-poor (10-20%) with the latter showing a smaller overall clast size (< 2 cm). Gradation between poorly-sorted muddy siltstone with dispersed clasts (facies Fmd) and diamictite (Dmm) occurs in several cores (cores 33, 37; Figure 3.8). The largest clast size observed is 10 cm and clast shape varies widely from angular to rounded. Measurement of clast long axis dip angles in diamictites shows a wide variation from flat-lying to steeply dipping clasts but preferred orientation of clasts parallel to bedding is apparent in chaotically-stratified intervals with 'flow banding'. In general, clasts are supported by a poorly-sorted muddy sand matrix (ranging from 60% sand, 30% silt and 10% clay to 30% sand, 50% silt and 20% clay) (Shipboard Scientific Party, 1999b). The sand fraction is compositionally immature showing more than 40% lithic fragments. An additional common component of diamictites are irregular blebs and stringers of dark-colored mudstone. Examination of thin sections of chaotically-stratified diamictite facies suggests that as much as 20% of the diamictite matrix consists of reworked mudstone. Shell fragments are common, including a complete barnacle valve in Core 28.

A distinctive feature of diamictites at Site 1103 is the presence of large numbers of light-coloured clasts of reworked marine mud (Figure 3.9B). Small mudstone clasts (< 2 cm diameter) (variably termed 'intraclasts', 'rip up clasts', 'silt clasts' or 'chips' in the literature; Pickering et al., 1989; Eyles et al., 1993) are a ubiquitous component of diamictite facies (Figure 3.8). In some intervals, they form up to 20% of the total clast population, resembling the 'clast breccias' of Pickering et al. (1989). Angular clast shapes suggest parent sediment was consolidated prior to reworking. Mud clasts contain a diverse, well-preserved diatom assemblage typical of continental shelves (e.g., *Stephanophyxis grunowii* and *Thalassionema*) but the surrounding diamictite matrix is barren apart from shell fragments (Shipboard Scientific Party, 1999b).

Chaotically-stratified, graded and massive sandstones (Sd, Sg, Sm)

Beds of chaotically-stratified, graded and massive muddy sandstone (Sd, Sg, Sm respectively; Figure 3.8) are between 2 cm and 3 m thick (Cores 37, 38; Figures 3.8, 3.9E, F). All sandstone facies are poorly sorted (65% sand, 25% silt and 10% clay) and gray in color. Isolated lithic clasts and mud clasts are scattered throughout and shell fragments are common. Massive facies are ungraded except for thin (< 5 cm) graded conglomeratic intervals at their base. Graded facies exhibit upwards reduction in texture (normal grading; Figure 3.8) but fine-grained bed tops were not recovered. Bed bases are sharp and erosional. Chaotically-stratified facies are distinguished by extensive soft-sediment deformation and evidence of incomplete mixing of different textural populations (Figures 3.9E, F). Core 27 shows parallel-laminated and graded sandstone beds showing extensive 'convolute' soft sediment deformation (Figure 3.8A). Beds of steeply-dipping graded sandstone occur in Core 33 interbedded with mudstone and diamictite (Figure 3.8A).

Mudstone (Fm, Fl)

Fine-grained facies at Site 1103 are represented by mudstones (Figure 3.8). The dominant facies is massive (facies Fm; Figure 3.9G) with a subordinate weakly-laminated facies (facies Fl; Figure 3.9H). Mudstones are very poorly sorted (5%-20% sand, 35%-70% silt and 10%-60% clay). Laminations have no systematic structure but are defined by thin (< 1 mm) streaks and sheared-out 'blebs' of siltstone and mudstone. Mudstones show transitions from massive to laminated facies with no systematic trends upcore (e.g. Core 31; Figure 3.8A). 'Floating' clasts are common in massive and laminated mudstone facies (facies Fmd and Fld respectively; Figure

3.8) and bioturbation is absent. Deformation structures, such as small-scale normal faults and dewatering structures, are present throughout (Figures 3.8, 3.10). Core 37 shows pillow structures and associated downward-penetrating dykes at the base of medium-grained massive sandstone (Figure 3.8). Core 31 is composed of interbedded laminated and massive mudstone with dispersed clasts, and diamictite (Figure 3.8). In other cores (e.g., Core 33; Figure 3.8) gradations occur between diamictite facies, mudstone with dispersed clasts, and mudstone lacking any clasts.

3.3.2 Environmental interpretation of lithofacies at Site 1103

Sedimentary facies recovered at Site 1103 are interpreted as sediment gravity flow deposits. Massive sandstone facies (facies Sm) are identified as the 'disorganized muddy sands' of Pickering et al. (1989) deposited either by very high density turbidity currents or very fluid sand-mud debris flows. A muddy matrix creates sufficient buoyancy to enable clasts to be freighted within the flow and grading is absent except for thin so-called 'coarse-tail' graded intervals at bed bases. Chaotically-bedded and massive poorly-sorted sandstones (facies Sd) record rapid deposition and 'freezing' of concentrated dispersions transported by sediment gravity flows. Graded sandstones (facies Sg) represent the B division of turbidites (Pickering et al., 1989).

Massive and irregularly laminated siltstones (facies Fm, Fl) also record rapid deposition from dense turbidity currents or muddy debris flows; lamination is probably generated when the flow progressively 'freezes' from the bed base to the top during deposition. Widespread soft-sediment deformation structures attest to rapid deposition and local fluidisation generated by rapid dewatering. Additional deformation structures, such as faults, probably result from post-depositional downslope creep.

The common presence of facies interpreted as sediment gravity flows at Site 1103 provides critical contextual evidence for the origin of massive diamictites. The latter are intimately interbedded with poorly-sorted massive and graded sandstones and siltstones (Figure 3.8) deposited from turbidity currents. Massive diamictites (facies Dmm; up to 4.2 m thick) are, consequently, identified as debris flows (debrites). Repeated flow is recorded by the interbedding of massive facies with beds of crudely-stratified diamictite with mudstone stringers (facies Dms; Figures 3.8, 3.9C, D). Muds were probably deposited on bed tops between flow events and were subsequently reworked and incorporated in later flows (e.g., Eyles, 1990; Visser, 1993).

3.3.3 Biofacies

Microfossils are rare at Site 1103 and though allowing ages to be identified offer few clues as to specific paleoenvironmental conditions. From the top of the hole to 210 mbsf several diatom species (*Actinocylus ingens, F. barroni, T. insigna, T. inura, T. oestrupii* and *T. torokina*) indicate a late Pliocene/Pleistocene age (Figure 3.7) (Shipboard Scientific Party, 1999b). Samples from approximately 290 mbsf contain late Miocene diatoms such as *Denticulopsis spp.*, *Nitzschia januaria*, and *Rouxia californica*. Most samples contain rare and reworked foraminiferal assemblages (Biofacies A; see above) (Figure 3.8). Mudstones in core 33 contain an in situ microfossil assemblage (Biofacies C).

3.3.4 Depositional setting and environmental history of Site 1103

On the basis of the presence of sediment gravity flow facies and seaward-dipping seismic reflectors (Figure 3.2), it is suggested that the lower part of the stratigraphy at Site 1103 is a record of deposition on a slope. A glacial source of debris (till?) is suggested by the presence of large numbers of clasts of diatom-bearing marine sediment and the presence of a mixed and abraded biofacies assemblage (Biofacies A). Associated poorly-sorted sandstone and mudstone facies were likely produced by downslope sorting of poorly-sorted debris flows in response to the onset of turbulence (e.g., Wright and Anderson, 1982; Walker, 1992). Such processes explain the upward transitions from clast-rich to clast-poor diamictite, and from diamictite to pebbly mudstone to mudstone (e.g., Core 33; Figure 3.8). In general, lithofacies at Site 1103 do not likely record protracted downslope flow because extended downslope transport results in the generation of better-sorted graded conglomerates, sandstones and siltstone turbidites (e.g., Wright and Anderson, 1982; Pickering et al., 1989; Walker, 1992; Eyles et al., 1993). Because of the very poor overall textural sorting shown by sandstones at Site 1103, close proximity to a glacial source is suggested and an upper slope setting can be inferred. Although poorly-dated (Figure 3.7), the seaward-dipping refelectors seen in the area of Site 1103 are too young to have suffered marked post-depositional tilting as a result of tectonic subsidence of the outer shelf and so are likely to be close to their original depositional attitude as upper continental slope 'foresets'.

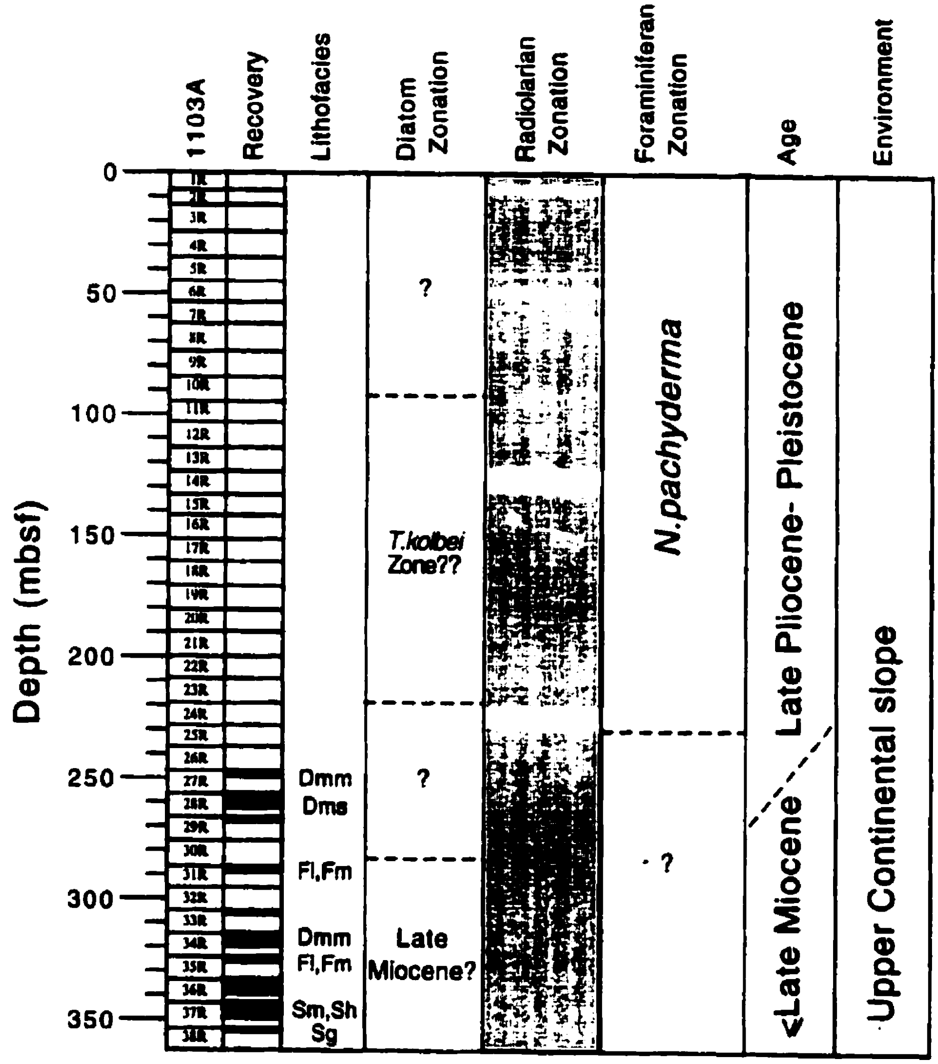

Figure 3.7. Summary figure for Site 1103 showing core recovery and generalized lithofacies. Biostratigraphic age control is provided by diatoms and radiolarian (stippling indicates barren intervals). For detailed graphic logs of cores see Figs. 8A, 8B.


27R
Clay Silt Sand
Sh
Dmm
Dms
Dmm
Dmm
Dms
Dmm
Dms
Dmm
Dms
Ⓐ
0
100 cm
28R
Clay Silt Sand
Dms
Dmm
Dms
Dmm
Dmm
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Dmm
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Dmm
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31R
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Dmm
Fmd
Fmd
Fld
Fmd. Fl
Fm, Fl
Fmd
Fl
Fm
Fl
32R
Sg
Ⓑ
33R
Clay Silt Sand
Fmd
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Ⓒ

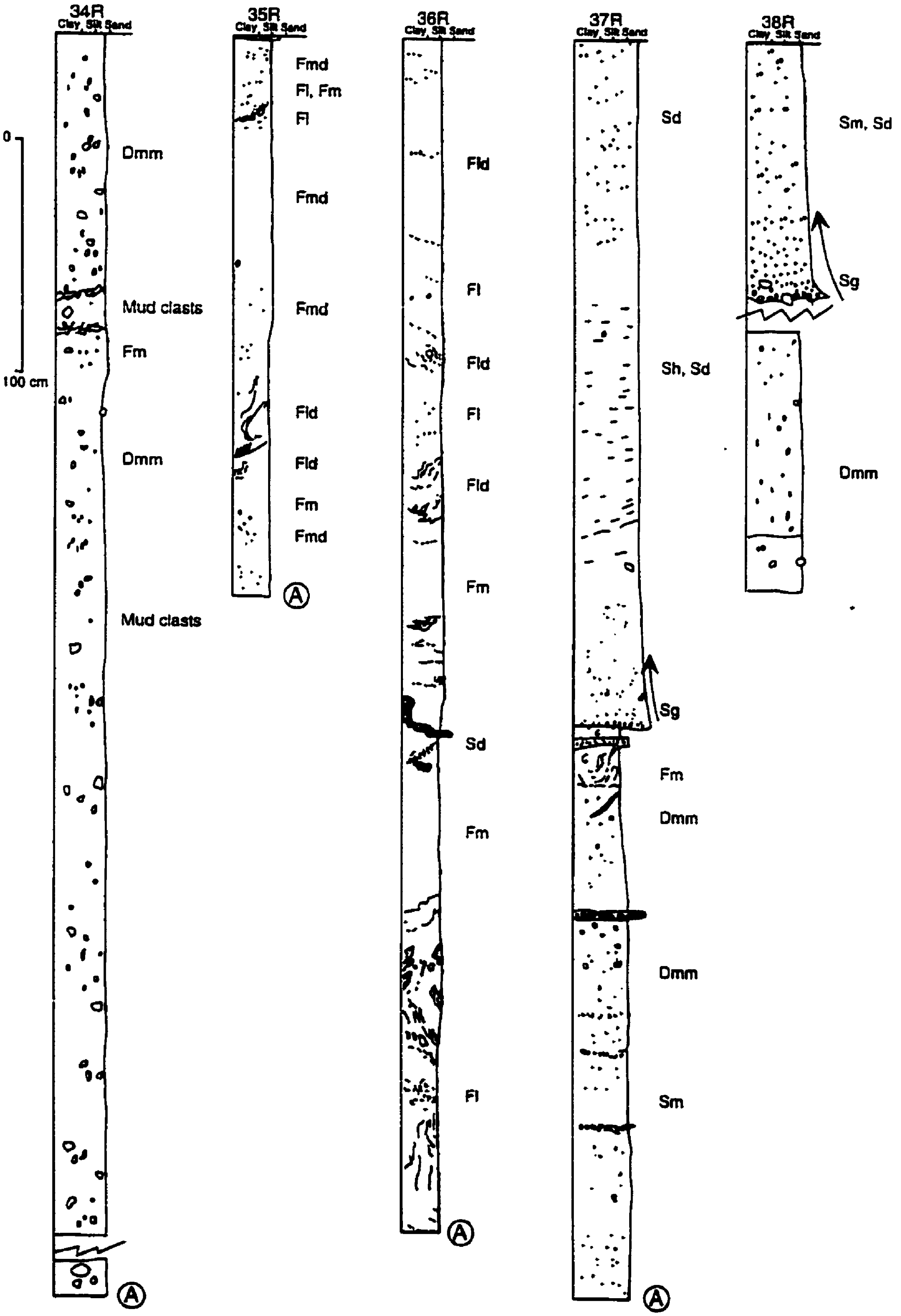
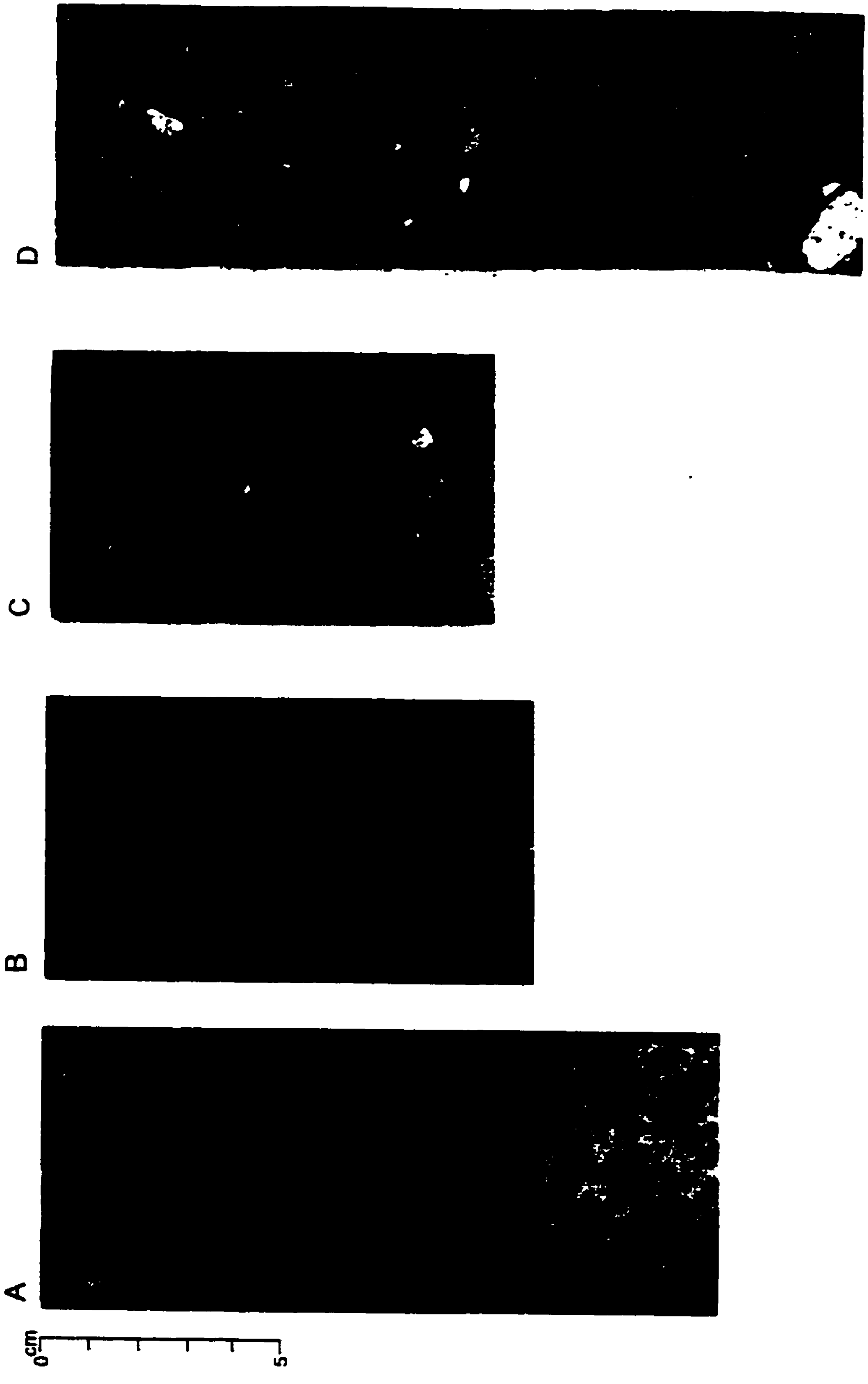


Figure 3.8. A, B. Graphic logs from representative cores at Site 1103 showing location of benthic foraminifer biofacies A, B and C. For lithofacies codes see Fig. 4.


D
C
B
A
0
cm
5

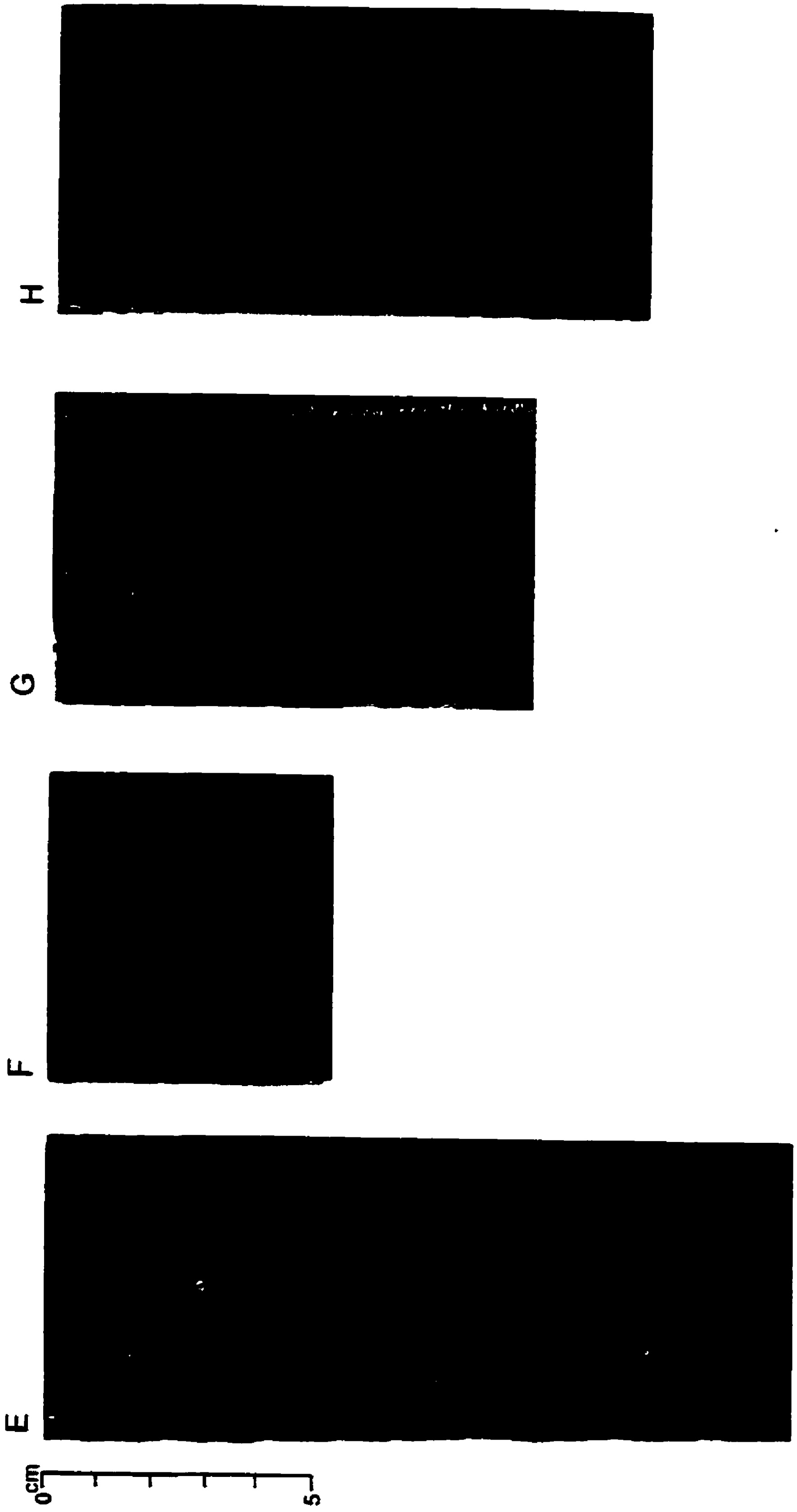

H
G
F
E
0 cm
5

Figure 3.9. Lithofacies at Site 1103.

A. Massive diamictite (facies Dmm) (Fig. 8): Site 1103A Core 27R Section 2 interval 9-23 cm.

B. Massive diamictite facies with numerous light-coloured silt clasts containing diatoms (Fig. 8): Site 1103A Core 34R Section 4 interval 43-53 cm.

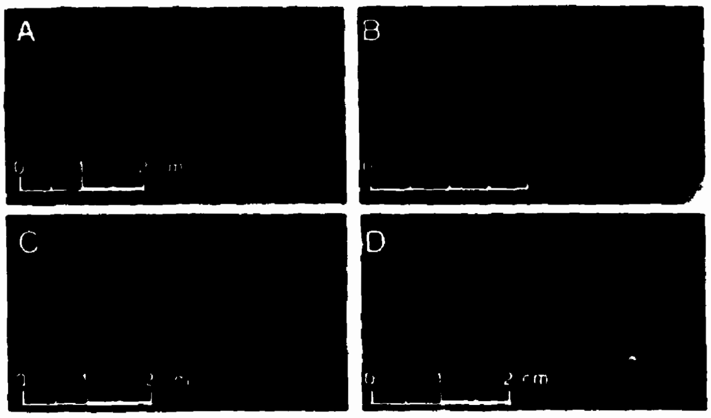
C. Chaotically-stratified diamictite (facies Dms) (Fig. 8): Site 1103A Core 28R Section 2 interval 83-92 cm.

D. Chaotically-stratified diamictite (Fig. 8): Site 1103A Core 28R Section 2 interval 24-41 cm.

E, F. Chaotically-bedded and massive sandstone (facies Sm, Sd) (Fig. 8): Site 1103A Core 38R Section 1 interval 53-67 cm; Site 1103A Core 38R Section 1 interval 40-45 cm.

G. Massive mudstone facies (Fm) (Fig. 8): Site 1103A Core 31R Section 1 interval 137-146 cm.

H. Weakly-laminated mudstone facies (facies Fl) (Fig. 8): Site 1103A Core 31R Section 1 interval 95-106 cm.



A. Site 1103A Core 35R Section 2 interval 39-43 cm
Vertical mud-stringers

B. Site 1103A Core 35R Section 2 interval 46-48 cm
Mud-stringers

C. Site 1103A Core 36R Section 3 interval 19-22 cm
Micro-faults of silty beds

D. Site 1103A Core 28R Section 4 interval 76-79 cm
Massive diamict

0 1 2 cm

Figure 3.10. Thin-section photomicrographs of diamictite and mudstone facies at Site 1103.

A, B. Deformed, laminated mudstone (facies fld): Site 1103A Core 35R Section 2 interval 39-43 cm; Site 1103A Core 35R Section 2 interval 46-48 cm.

C. Microfaults in deformed laminated mudstone (facies fld): Site 1103A Core 36R Section 3 interval 19-22 cm.

D. Massive diamictite: Site 1103A Core 28R Section 4 interval 76-79 cm with numerous darker coloured mudstone blebs.

3.4 Discussion

It must be emphasized that core recovery by ODP Leg 178 from the Antarctic Peninsula Pacific continental margin was poor and this necessarily constrains interpretation. Nonetheless, significant litho- and biofacies information was derived from Sites 1097 and 1103 that improves current understanding of depositional processes leading to the formation of glaciated continental margin topsets and foresets in Antarctica. The broader implications of the results from Sites 1097 and 1103 are briefly identified below.

3.4.1 Origin of topsets

Bart and Anderson (1995) argued for a Middle Miocene (after 15 Ma) onset of glaciation along the Antarctic Peninsula (possibly related to uplift of the Graham Land plateau; Elliot, 1995). More recently, Dingle and Lavelle (1998) have suggested glaciation began around 10 Ma. Regardless, all workers are agreed that initial glaciation was characterised by restricted ice cover over the Peninsula resulting in limited continental margin progradation. A second stage of larger-scale glaciation and longer-duration glacials commenced at the Miocene/Pliocene boundary (c. 5 Ma) when a phase of enhanced slope progradation ensued (Bart and Anderson, 1995).

Sedimentological and biofacies data at Site 1097 indicate that topsets are constructed of substantial thicknesses of till reflecting large-scale subglacial reworking of pre-existing glacial and marine sediment across the shelf during ice sheet expansion and decay (Figure 3.3A). These data clearly indicate that the Antarctic Ice Sheet reached the edge of the Antarctic Peninsula

Pacific continental shelf during the Early Pliocene (Figures 3.3A, 3.7). ten Brink et al. (1995) suggested that large amounts of marine sediment were retransported subglacially from Antarctic inner shelf basins to the outer shelf and upper slope. This model is clearly supported by Leg 178 data at Site 1097. Work on Pleistocene mid-latitude ice sheets has shown that ice sheet margins that rest on relatively 'soft' deformable beds give rise to a low surface profile and fast ice flow ('streaming'; e.g. Boulton, 1996). This model has recently been employed in interpretation of incoherent seismic facies within topsets of the glaciated southeast Greenland continental margin (Clausen, 1998). It has previously been suggested that such conditions existed on the Antarctic Peninsula shelf (e.g., Pudsey et al., 1994; Bart and Anderson, 1995) and there has also been much discussion of depositional mechanisms (Alley et al., 1989; Vanneste and Larter, 1995). To date, however, such till facies have not yet been recovered by drilling and so data from Site 1097 are significant. The occurrence of flute fields on the APPcm shelf adjacent to Site 1097 (Pudsey et al., 1994) provides additional evidence of 'soft-bed' conditions below the last ice sheet across the shelf because such bedforms are associated with a deforming subglacial bed (e.g., Boulton and Hindmarsh, 1987; Boulton, 1996; Boyce and Eyles, 1991; Shipp et al., 1999).

Previous work has suggested that the APPcm shelf aggrades during interglacials and that the slope progrades only during major glaciations (Larter and Barker, 1989; Larter and Cunningham, 1993). Data from Site 1097 near the shelf edge clearly contradict this model by demonstrating that topsets are composed of substantial thicknesses of poorly-sorted diamictite (till) deposited during shelf-wide glaciation. We note that the conclusions of these workers was not rooted in any sedimentological data but was based solely on interpretation of seismic data restricted to seismic dip lines. A more detailed seismic investigation of the APPcm shelf and slope was presented by Bart and Anderson (1995) using both dip and strike profiles. Their data show multiple unconformities with topset successions and considerable along-strike variation in geometry of foresets. Bart and Anderson (1995) suggested that chaotic seismic facies are tills and this is supported by lithofacies and biofacies data from topsets at Site 1097; the apparent aggradation of successively thicker intervals of till at this site (Figure 3.3A) also supports their model of a trend toward longer duration glaciation of the Antarctic Peninsula shelf since the late Miocene.

The depositional model identified above stresses that aggradation of topsets occurs by subglacial deposition of till that is derived largely by the reworking and retransport of marine sediment. If correct, then it suggests that the topsets of the APPcm shelf are unlikely to contain a high resolution record of climate because interglacial marine strata are extensively reworked during ice expansion to the shelf edge.

3.4.2 Origin of foresets

The sedimentary record at Site 1103 provides insight into the fate of sediments at the shelf edge where slope foresets prograde by the reworking of glacial debris (till) and marine sediments as debris flows and turbidity currents. The preservation of hemipelagic sediments within slope foreset stratigraphy suggests that the slope offers a more attractive target for a high resolution record of climatic and oceanographic change. Similar successions have been recovered by piston coring of the modern Antarctic continental slope (Anderson et al., 1979) and are widely reported from many other Pleistocene glacially-influenced continental margins (e.g. Hill, 1984; Vorren et al., 1989; Stoker et al., 1991; Aksu and Hiscott, 1992; King et al., 1998) and also from the pre-Pleistocene record (Visser, 1983; Miall, 1985; Eisbacher, 1985; Young and Gostin, 1991; Eyles, 1990, 1993, Eyles and Lagoe, 1990; Eyles et al., 1991; Eyles and Lagoe, 1998; McB Martin, 1999). This large literature suggests, in general, that episodes of shelf-edge glaciation result in the progradation of areally-extensive, voluminous 'foreset' successions of stacked debris flows and hemipelagic deposits. Indeed, there are many similarities between strike-oriented, seismic profiles of slope deposits published by King et al. (1998) from the northern North Sea continental margin (e.g., their Fig. 2) and those of Bart and Anderson (1995) taken across foresets of the Antarctic Peninsula (e.g. their Figs. 6a, 6c). A detailed comparison of the long-term evolution of topsets and foresets along the Antarctic Peninsula Pacific continental margin with other northern hemisphere glaciated continental margins is not yet possible. However, a very similar style of continental margin growth has apparently occurred along the southeast Greenland margin (Clausen, 1998), the northwestern Norwegian margin (Saettem et al., 1992) and along the eastern Canadian margin (Hiscott and Aksu, 1994). This suggests a commonality of depositional processes along glacially-influenced continental margins, regardless of latitude.

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CHAPTER 4

CONCLUSIONS AND FUTURE RESEARCH

Conclusions and Future Research

After almost 50 years of detailed study along the Antarctic continental margin understanding of the depositional processes that have been active on the Antarctic shelf and slope have evolved rapidly in the last decade. Geophysical techniques presented a regional picture of subsurface stratal geometry and deep drilling projects provided cores which could be used to ground-truth seismostratigraphic models of margin evolution. Antarctica is currently a unique polar environment but present conditions may not be representative of the ancient continental margin where evidence suggests large fluxes of sediment were transported during glacial advances.

Study of the Antarctic margin has recently benefited from integration of multiple databases (geophysics, sedimentology, biostratigraphy) and from advances in glacial sedimentology from studies of Pleistocene and pre-Pleistocene glaciated basins in the northern hemisphere. Such an approach was followed during Ocean Drilling Program Leg 178 to the Pacific-facing margin of the Antarctic Peninsula (Feb.-April 1998). Core recovery by ODP Leg 178 was poor but integration of biofacies, lithofacies and seismic profiles resulted in improved understanding of depositional processes leading to the formation of glaciated continental margin *topsets* and *foresets*.

Shelf topsets aggrade through deposition of deformation till reflecting large-scale subglacial reworking of pre-existing glacial and marine sediment across the shelf during ice sheet expansion and decay. Topsets therefore are unlikely to contain a high resolution record of climate because interglacial marine strata are extensively reworked during ice expansion to the shelf edge. Slope foresets prograde by the reworking of deformation till and marine sediments as debris flows and turbidity currents. The preservation of hemipelagic sediments within slope foreset stratigraphy suggests that the slope offers a more attractive target for a high resolution record of climatic and oceanographic change. This model is in agreement with data from northern hemisphere glaciated margins (Clausen, 1998; Stoker et al., 1991; King et al., 1998; Aksu and Hiscott, 1992). This suggests a commonality of depositional processes along glacially-influenced continental margins, regardless of latitude. More detailed inter-hemispheric comparisons should now be made and will comprise part of the author's PhD thesis.

Finally, as knowledge of diamictite-forming processes on glacial and non-glacial continental margins has expanded (Eyles, 1993) it is evident that massive diamictite facies are deposited by a wide range of processes. Re-examination of Leg 119 (Prydz Bay, 1988) cores by the author indicates that diamictites from the slope and shelf are better interpreted as debris flows and deformation till. This depositional model will be further tested by the author during ODP Leg 188 which will drill the Prydz Bay continental margin (Jan.-March 2000). Leg 119 and 188 data will be integrated and presented as a PhD thesis by the author.

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APPENDIX A Glossary

basal debris zone The region at the base of a glacier that entrains and transports sediment *englacially*.

basal till includes both *lodgement* and *melt-out* tills.

debris flow A moving mass of rock fragments, soil and mud.

debrite The lithified equivalent of debris flow.

deformation till Subglacial deposit formed when a glacier overrides soft, unlithified sediments. Resulting high pore water pressures gives rise to subglacial shearing and deformation of the sediments (Boulton, 1996; 1990).

diamictite A comprehensive, nongenetic term proposed by Flint et al. (1960) for a nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes.

distal glaciomarine sediment Deposition of predominantly biogenic sediments with the addition of a minor ice-rafted component distal from the ice margin.

drift A general term for all rock material transported by glaciers and deposited directly from the ice or through the agency of meltwater. It is generally applied to Pleistocene deposits.

englacial Contained, embedded or carried within the body of a glacier or ice sheet.

foreset A *foreset* bed; In reference to Antarctica, one of the seaward-dipping layers deposited upon or along an advancing frontal slope such as a continental slope.

glacial marine sedimentation The accumulation of glacially-eroded, terrestrially-derived sediment in the marine environment. Sediment may be introduced by fluvial transport, ice-rafting, as an ice-contact deposit, or by eolian transport. Deposits can be divided into a number of glacial marine facies (Molnia, 1983).

glacigenic A deposit of glacial origin.

grounding line The point where a glacier or ice shelf begins to float.

hemipelagic Deep sea sediment which usually accumulate near the continental margin and its adjacent abyssal plain.

lodgement (till) Deposition by active "plastering on" of subglacial debris by grounded ice, often containing stones oriented with their long axes generally parallel to the direction of ice movement.

melt-out (till) Till derived from slow melting of thick masses of debris-rich stagnant ice buried beneath sufficient overburden to inhibit deformation under gravity, thus preserving structures derived from the parent ice (Boulton, 1970).

paleoslope The direction of initial dip of a former land surface; especially the regional slope of a large ancient physiographic unit such as a continental slope.

polar glacier A glaciers which is frozen to its base and moves by internal deformation.

proglacial Immediately in front of or just beyond the outer limits of a glacier or ice sheet, generally at or near its lower end; said of lakes, streams, deposits and other features produced or derived from the glacier ice.

proximal glaciomarine sediment Deposition of marine sediments, e.g., sands and muds, depending on water depth, with the addition of a high proportion of ice-rafted material following calving of either a floating or grounded glacier tongue.

subglacial Formed or accumulated under a glacier or ice sheet.

temperate glacier A glacier that moves by sliding across its bed as a result of pressure-melt and characterized by abundant supraglacial, englacial and subglacial water.

till Unstratified, poorly-sorted material, deposited directly by and underneath a glacier without post-depositional reworking and consisting of a heterogeneous mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape.

till delta Terminology used by Alley et al. (1989) to describe sediments deposited at the grounding line of an ice stream. This term was informally introduced to emphasize the 'delta-like' nature of the deposits and dominance of till in the topset beds.

till tongues Large and thick acoustically massive sedimentary bodies observed in seismic profiles from glaciated continental margins and characterized by poorly sorted, overconsolidated sediment interpreted as debris flows.

topset A *topset* bed; In Antarctica, one of the nearly horizontal layers deposited on surface of the continental shelf; it truncates or covers the edges of the seaward-dipping foreset beds.

waterlain till Deposition by continuous rain-out of basal glacial debris from a floating glacier tongue just seaward of the grounding line, but without significant reworking by bottom currents or slumping. Now know to be insignificant as basal debris is rapidly exhausted.

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