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Late Eocene signals of oncoming Icehouse conditions and changing ocean circulation, Antarctica

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ABSTRACT

The end of the Eocene greenhouse world was the most dramatic phase in the long-term Cenozoic cooling trend. Here we use 75,000 km of multi/single channel seismic reflection data from offshore Prydz Bay, Antarctica, to provide new insight on the Paleogene stratigraphic transition from greenhouse to icehouse conditions and reorganizing the ocean circulation changes that were invigorated by the cooling and glaciation. We identify a new prominent Paleogene transitional phase (Greenhouse to Icehouse) preserved in the deep-water sedimentary record by correlating from shelf to the continental slope. The occurrence of mega-Mass Transport Deposits (MTDs) on the slope during an early stage in the transition suggests significant instability and collapse of the upper part of the continental margin. A second stage of the transition is represented by the growth of a well-defined set of continental slope clinoforms. We estimate the formation age of the MTDs and clinoforms to be around Eocene-Oligocene Transition. The formation of the clinoforms in the transitional phase indicates sea level has risen, and large volumes sediment delivered to the margin by marine-terminating glaciers on the shelf. Finally, a subsequent marked migration of the margin depocenter toward the west and northwest, attests the onset of drift sedimentation and full glacial conditions, suggesting a more vigorous ocean circulation as the Earth entered the icehouse conditions after the Eocene-Oligocene boundary.

1. Introduction

Sediment archives from the Southern Ocean and East Antarctic continental margin provide evidence for the onset and evolution of the East Antarctic Ice Sheet (EAIS). Ice-rafted debris and clay mineral assemblages provide direct evidence that regional marine-terminating ice existed in the late Eocene (Ehrmann and Mackensen, 1992; Escutia et al., 2005; Gulick et al., 2017; Passchier et al., 2017). Stable isotopic data for the early Cenozoic (Paleocene to Eocene) also show a long-term pattern of cooling (Tripati et al., 2005; Miller et al., 2005; Zachos et al., 2008) leading to rapid expansion of the Antarctic continental ice sheet in the latest Eocene to earliest Oligocene (Coxall et al., 2005; Carter et al., 2017; Galeotti et al., 2016). However, questions remain about the mechanisms involved in ice sheet formation, the dynamics of ice growth and the feedbacks to the Earth system and ocean circulations.

Antarctic glaciation caused ocean circulation changes between late-middle Eocene to earliest Oligocene (Goldner et al., 2014). The oceanographic isolation of Antarctica started at least 34 My ago as the Drake Passage and Tasmanian gateways opened (Stickley et al., 2004; Eagles and Jokat, 2014). The opening of these two crucial gateways permitted the onset of a precursor of Antarctic Circumpolar Current (ACC), whose action is evident from contourite deposits and from an Eocene-Oligocene (E-O) hiatus at locations throughout the Southern Ocean (Florindo et al., 2003). Although some ocean circulation models show less sensitivity to the opening of gateways (Hill et al., 2013; Lauretano et al., 2021), and the time of initial opening of Drake Passage is still under debate (Eagles and Jokat, 2014; Maldonado et al., 2000), the Drake Passage is undoubtedly a key towards understanding the development of modern oceanic circulation patterns and their implications for ice sheet growth and decay (Livermore et al., 2005; Pérez et al., 2021; López-Quirós et al., 2021).

The vigorous current systems in the Southern Ocean play a critical role in redistributing glacially-derived sediments and depositing them in sediment drifts that contain records of long-term environmental change. Depositional signatures in sedimentary successions along the Antarctic margin provide Neogene records of Antarctic glaciation and its relationship with global climatic and

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oceanographic change (Escutia et al., 2005; Hernández-Molina et al., 2009; Gohl et al., 2013; Huang and Jokat, 2016; Huang et al., 2022; Uenzelmann-Neben et al., 2022). However, detailed knowledge of the timing and paleoenvironmental implications of ice growth and ocean circulation during the transition from greenhouse to icehouse are limited (Lear et al., 2008; Galeotti et al., 2016).

The Cenozoic sediments that are preserved within the Prydz Bay region contain important information about the timing and magnitude of EAIS build-up and decay, as well as the changing configuration and varying intensity of deep water circulation (Huang et al., 2020). Previous data on the Cenozoic strata of Prydz Bay shelf (Barron et al., 1991; Cooper and O'Brien, 2004; Passchier et al., 2017) from Ocean Drilling Program Legs 119 and 188 sites allow us to evaluate the timing of non-glacial to glacial paleoenvironmental change. However, a knowledge gap exists in this transitional period from records in the deeper waters offshore due to the lack of direct deep-water Paleogene sediment cores to provide a precise chronology of sedimentation and to constrain seismic stratigraphic correlation.

The aim of the current work is to establish a new shelf-to-basin correlation to bridge the knowledge gap by 1) interpreting the nature of the Greenhouse to Icehouse transition from the character of the stratal succession offshore Prydz Bay and Mac. Robertson Land, 2) describing the key depositional elements that developed during the transition in this area, particularly an extensive field of mass transport deposits (MTDs) and subsequent margin clinoform sets and how they are probably a response to glacial advances on the shelf, and 3) creating isopach (thickness) maps, identifying deposits related to bottom-current activity at the base-of-slope on the margin and relating them to changes in sediment supply and ocean circulation. Overall, our current study provides new evidence of remarkable changes in the importance of both glacial and ocean-current processes in the transition from greenhouse to icehouse conditions. A database consisting of two-dimensional (2D) seismic data (a network of 75,000 km of previously acquired multi- and single-channel seismic reflection data) and data from ODP Legs 119 and 188 sites are the primary source for this study.

2. Regional setting

Prydz Bay is the third largest embayed shelf of the Antarctic margin and contains a continuation of the 50 km-wide Lambert Graben that extends 1000 km inland to the Gamburtsev subglacial mountains (Ferraccioli et al., 2011) (Fig. 1). The Lambert Glacier now drains ice from a catchment that includes the Gamburtsev subglacial mountains, a key nucleation point for the EAIS when they were exposed at the surface in late Eocene times (Jamieson et al., 2005). Subglacial landscape analyzes indicate a complex arrangement of sites and patterns of erosion and sediment transport between the Gamburtsev Mountains and the continental shelf, slope, and rise (Ferraccioli et al., 2011; Rose et al., 2013). Today the broad pattern of ice and sediment transport towards the bay is controlled by the graben's morphology, a result of Permian rifting with possible extensional reactivation late in the Cretaceous (Hambrey et al., 1991; Ferraccioli et al., 2011). The present shelf region is covered by seasonal sea ice and is bounded to the east by Princess Elizabeth Land and to the west by Mac. Robertson Land (Fig. 1). The geomorphology and margin architecture of Mac. Robertson Land and Prydz Bay contrast strongly (Huang et al., 2020). The Prydz Bay margin is characterized by a broad shelf ($\sim$250 km), cut by the large glacial trough of the Prydz Channel, and fronted by a low continental-slope gradient ($<2°$). The Mac. Robertson Land continental slope is steeper (4–6°), the shelf is narrower (60–80 km) and is cut by smaller glacial troughs (e.g., Nielsen Basin, Fig. 1). The combinations of these enduring morphodynamic features and glacial processes exert fundamental control on onshore-offshore depositional patterns in the Prydz Bay region.

Ocean circulation in the Prydz Bay region is complex. Deep-water movements on the continental slope and rise are attributed to three large-scale ocean systems: the Polar Current, moving westward near the shelf edge; the Antarctic Divergence, producing cyclonic gyres over the continental slope and inner rise; and the Antarctic Circumpolar Current, moving eastward over the outer rise and beyond (Cooper and O'Brien, 2004). The water mass that occupies most of the ocean volume in the region is Circumpolar Deep Water. This is overlain by a cap of fresher Antarctic Surface Water that is 200–400 m in thickness that becomes stratified in summer into a warmer upper layer overlying a cooler Winter Water layer. Recent studies have also confirmed that Prydz Bay is another region that present-day Antarctic Bottom Water (AABW) forms. AABW is cold, dense water that spreads throughout the abyssal layer of the world ocean and was at one time thought to originate almost exclusively in the Weddell and Ross seas (Orsi et al., 1999). Unlike the previously identified sources of AABW, which require the presence of an ice shelf or a large storage volume, the bottom water production at the Cape Darnley polynya at Prydz Bay is driven primarily by the flux of salt released during sea-ice formation (Ohshima et al., 2013) according to ship-based observations and numerical modeling. The interaction of the near-seafloor currents (e.g., downslope density currents and along-slope ocean currents) is believed to control slope and rise sediment deposition in the Prydz Bay region (Kuvaas and Leitchenkov, 1992; Huang et al., 2020).

3. Data and methods

2D seismic data and bathymetry The seismic-reflection lines used in this study are a compilation of data sets available from Scientific Committee for Antarctic Research (SCAR) Seismic Data Library System (SDLS), and include ten surveys (BMR33, TH84, TH89, TH99, RAE39, RAE 46, RAE 48, RAE 52, GA228, GA229) acquired by Australian, Russian, and Japanese research cruises (Table 1) and the International Ocean Drilling Program Legs 119 and 188. Approximately 75,000 km of fair to good quality seismic data were recorded. The seismic lines were downloaded from the SDLS (http://sdls.ogs.trieste.it) in SEG-Y format and converted to a common georeferenced system for import to Petrel E&P software platform for further interpretation. Metadata defining the acquisition parameters for each survey can also be found in the SDLS data library and the Table 1. All the vertical scales for seismic profiles shown in the study are two-way travel time.

Establishing a likely chronology on the margin succession The continental shelf and upper slope of the Prydz Bay margin have been built by a thick Cenozoic stratigraphic succession exhibiting mainly progradational and aggradational, long-term sediment stacking patterns. Despite the lack of Paleogene sediment cores to provide a precise chronology, an interpreted shelf-to-basin stratal correlation is possible based on the 75,000 km of multi/single channel seismic reflection data and information from ODP legs 188 and 119 over Prydz Bay and offshore Mac. Robertson Land (Fig. 2). The sites drilled and logging techniques are detailed in Barron et al. (1991) and O'Brien et al. (2001). In particular, results from ODP drill sites 739, 742 and 1166 on the shelf and slope together provide a detailed record of the Eocene-Oligocene transition on the continental shelf of Prydz Bay. However, the oldest deep water sediment cores were determined to be of early Miocene age (Shipboard Scientific Party, 2001), and this presents challenges in assigning ages to the pre-Miocene sediments. Using the rich seismic dataset, we are able to pick key seismic stratigraphic boundaries on the basis of their seismic geomorphology and inferred sequence

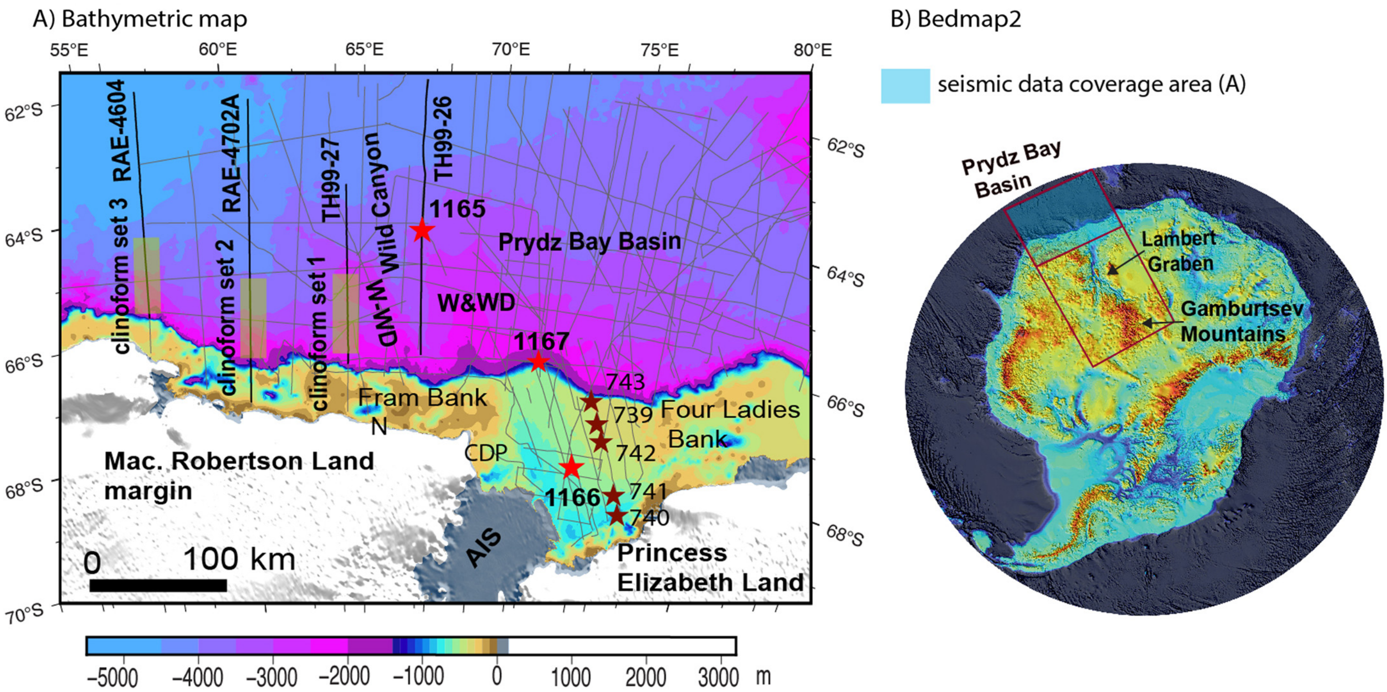

Fig. 1. A: Bathymetry of the Prydz Bay margin from IBCSO (Arndt et al., 2013); B) subglacial topography (Bedmap 2; Fretwell et al., 2013). AIS: Amery Ice Shelf. N: Nielsen Basin. CDP: Cape Darnley Polynya. W & WD: Wild and Wilkins Drift, W-WD: West-Wild Drift. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Table 1
Seismic data information.

Line name	Source (channel)	Receiver	Group/shot interval (m)	Sample rate (ms)	Recording Length (s)	Institution / Country	Time (years)
BMR33	Air Guns (8.2 L)	6	25 or 50 /50	2	6 to 8	AGSO / Australian	1982
TH84	2 Water Guns (13.1 L)	24	25/50	4	5	JNOC AND GSJ / Japan	1984
TH89	2 Water Guns (13.1 L)	24	25/50	4	4 to 5	JNOC / Japan	1989
TH99	16 GI Guns (65.55 L)	240	12.5/50	2	9.5	JNOC / Japan	1999
RAE39	2×2 Air Guns (40 L)	48	50/100 or 200	4	4 or 7 or 8	PMGE / Russia	1994
RAE46	2 Air Guns (20 L)	72	50/50	2	7	PMGE / Russia	2001
RAE48	2 Air Guns (40 L)	240	12.5/50	2	13	PMGE / Russia	2003
RAE52	2 Air Guns (48.5 L)	352	12.5/50	2	11 or 13	PMGE / Russia	2007
GA228	30 Air Guns (60 L)	288	12.5/50	2	16	GA / Australia	2001
GA229	30 Air Guns (60 L)	288	12.5/50	2	16	GA / Australia	2002

Notes: AGSO – Australian Geological Survey Organization; JNOC – Japan National Oil Corporation; GSJ – Geological Survey of Japan; PMGE – Polar Marine Geosurvey Expedition; GA – Geoscience Australia.

stratigraphy. We attempt to tie these key surfaces to chronostratigraphically constrained borehole data of ODP legs 119 and 188, to establish the chronostratigraphic framework on the margin (Fig. 2).

4. Results

4.1. Seismic units

Seismic stratigraphy allows the identification of three major seismic units (SU1-SU3) bounded by four key horizons (seafloor and U1-U3) in the Mac. Robertson Land and Prydz Bay continental slopes and rises. In seismic profiles these key horizons appear as erosion surfaces with high-amplitude reflections with good lateral continuity (Fig. 2). The three seismic units vary in thickness and form depocenters parallel to the slope, and are further characterized by distinguished seismic reflection patterns representing different depositional histories.

The U1 Horizon (acoustic basement) is developed throughout the study area and separates the acoustic basement from the overlying sedimentary cover. The horizon is irregular, probably as result of block faulting, and separates chaotic reflections in the basement below from the stratified sequence above (Fig. 2). The *lower key unconformity* U2 is expressed as a sharply unconformable erosional boundary between the underlying undulating sequence and the overlying sequence that contains many lenticular units with chaotic reflection characteristics. The underlying stratal succession shows subparallel reflections of medium-high amplitude in the deeper part of the basin and lies on faulted crystalline basement of low to medium reflective character on the continental slope (Fig. 2). The *upper key unconformity U3* is marked by a distinct erosion surface, which is a traceable basin-wide, continuous reflector with strong seismic amplitude. In deep water, U3 occurs close U2 and the two unconformities record the most marked change in the stratigraphic configurations through the entire sedimentary succession. The present-day seafloor morphology of the area shows numerous channels and sedimentary ridges, which have about a kilometer of relief (Figs. 3, 3A).

4.1.1. Seismic Unit 1

Seismic Unit 1 (SU1) is bounded below by the acoustic basement (U1) and above by an unconformity U2 (Fig. 2). The succession below the U2 unconformity was deposited on a faulted crystalline basement (U1). This unit shows a low to medium reflective character on the lower slope (Fig. 2) and parallel-subparallel

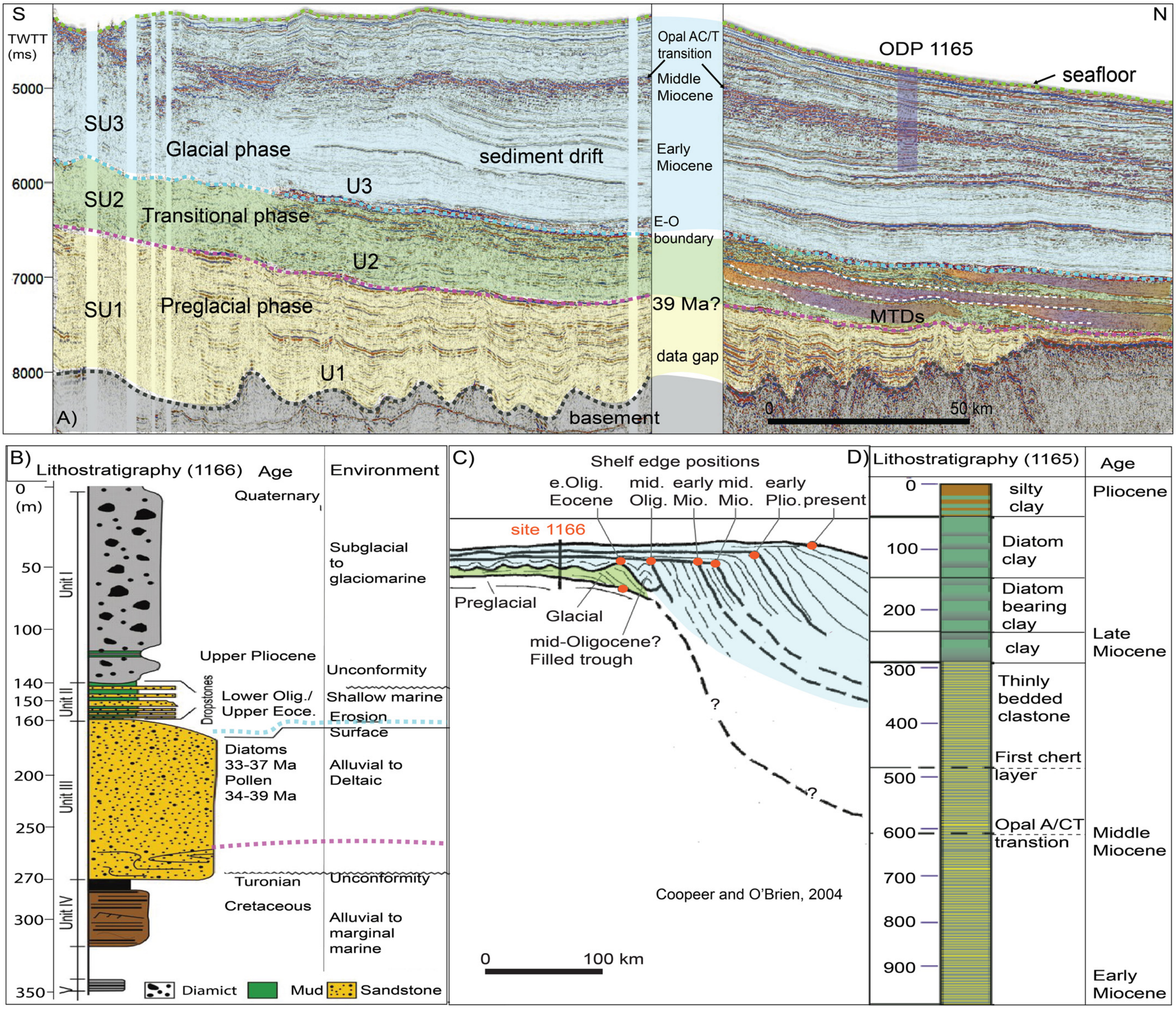

Fig. 2. Seismic profile TH99-26 (A) and lithological logs showing proposed correlation between ODP sites 1166 (B) and 1165 (D) (for locations see Fig. 1). Thick (>100 m) poorly sorted sand (mix of angular and rounded grains) is recorded in unit III of ODP Site 1166 and attributed to a glacio-fluvial braid-plain outwash system on the shelf (Shipboard Scientific Party, 2001). C) The existing seismic stratigraphy modified after Cooper and O'Brien (2004).

reflection of medium-high amplitude in the deeper water (Figs. 1, 2). The basement shallows toward the deep basin with a thin (<1 km) sediment cover in the deep-water area, but with very thick (up to 3 km) sediment accretion on the slope in front of the shelf (Figs. 1–3).

4.1.2. Seismic Unit 2

Seismic Unit 2 (SU2) is bounded below by the unconformity U2 and by the unconformity U3 above (Fig. 2). SU2 is characterized by northward dipping high-amplitude reflections that separate into two sediment packages, the lower one showing a chaotic seismic pattern, the upper one showing a inclined prograding wedge with parallel low-amplitude reflections. SU2 thins toward the basin from 1800 m on the continental slope to 200 m on the basin floor (V=2500 m/s, O'Brien et al., 2001) (Figs. 3, 4A).

In some seismic profiles, the lower part of SU2 consists of ca. 500 m of sediments with a chaotic seismic reflection pattern (Figs. 2, 3) that is regionally traceable in the deep-water region. This prominent zone of chaotic reflections is interpreted as large-scale MTDs (Fig. 3). Overlying the MTDs, a prograding wage is observed (Fig. 3A). The downslope and lateral seismic facies variability in the prograding wedge is consistent with a clinoform interpretation. The clinoforms built out perpendicular to the continental margin and show a distinct pattern of well-organized prograding and downlapping depositional units (Figs. 4A,B). The sets of clinoforms are confined between two apparently erosional surfaces and they show marked toplap reflector truncations that may be a sequence boundary unconformity (Fig. 4). Clinoforms here extend about ~75 km in the dip direction, ~70 km along depositional strike, and are up to 0.5 km thick, with a volume of 3375-5625 km^3 (Figs. 1, 3, 4).

The clinoforms are discrete oblique growth increments of a northward prograding continental margin (Fig. 3B). They are accretionary units of the basin-margin to deeper water foreset slope areas and eventually to the basin floor, ie they are the margin building blocks. Seismic amplitudes are high on the foreset segments of the clinoforms, but low to moderate on the muddier bottomsets. The truncations at the tops of the clinoform sets indicate

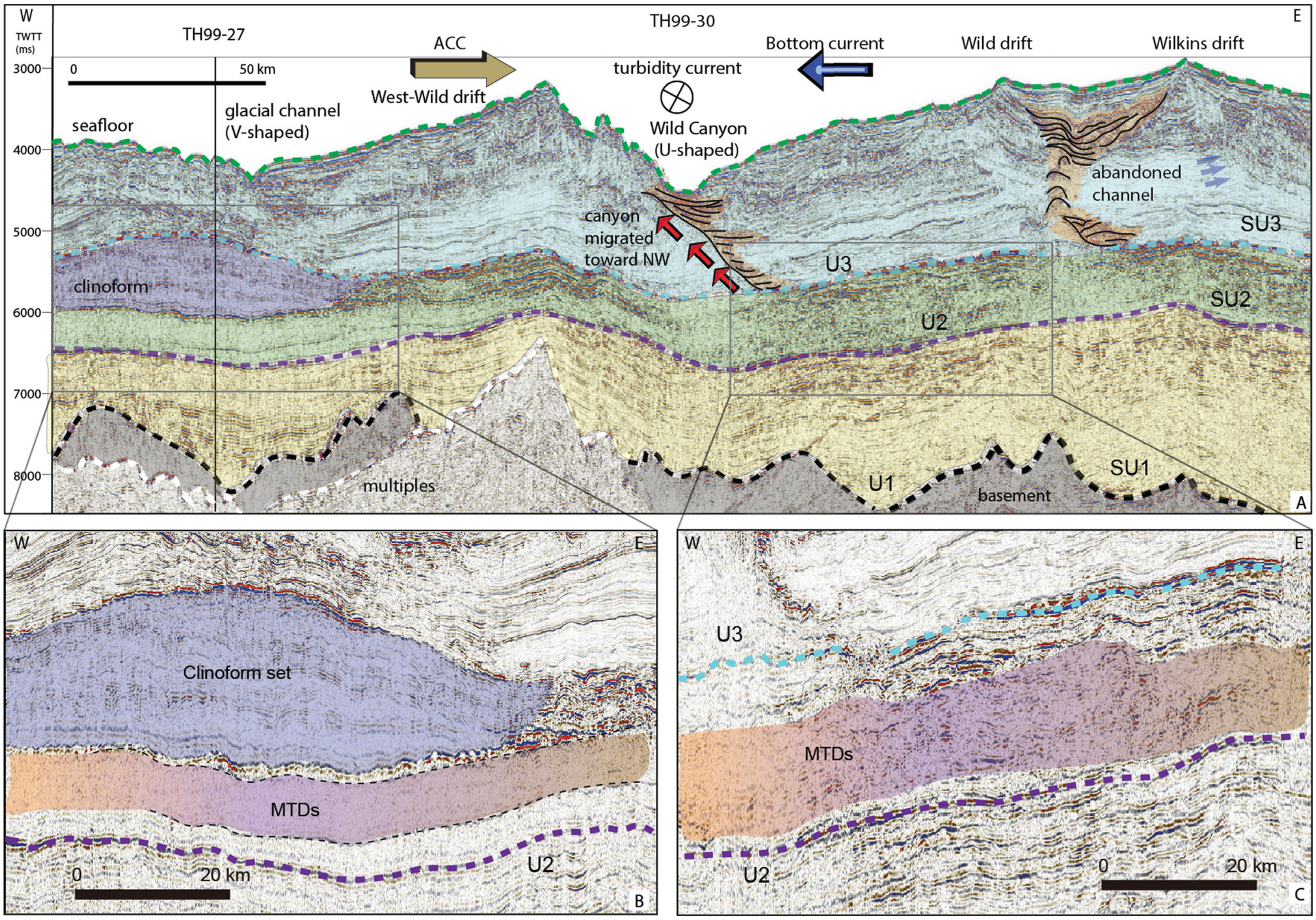

Fig. 3. A) Seismic line TH99-27, located at West Wild Drift (Fig. 1). Box shows location of interpretation in B. B) Interpretation of Well-preserved clinoforms of set 1 on the slope, perpendicular to Mac. Robertson Land coast; C) Mass Transport Deposits (MTDs) perpendicular to the Mac. Robertson Land coast.

significant downcutting (Fig. 3B). The topset units are therefore hummocky and discontinuous laterally. The gradients of the clinoforms slopes are relatively low (typically 0.5 to 1 degree), but with internal truncations indicating channeling or further slight changes in growth trajectory. The slope segments of the clinoform sets, seismically less distinct than the topset segments, are often characterized by toplap truncations (Fig. 3B). Slope reflections converge into bottomset strata displaying a sheet-like geometry.

4.1.3. Seismic Unit 3

Seismic unit 3 (SU3), the youngest sedimentary unit, is bounded by unconformity U3 at its bottom and by the seafloor on the top (Fig. 2). Distinct changes of seismic reflection character are observed in this unit, implying or at least hinting at a contrast in process stratigraphy (Fig. 2).

Within SU3 we observe three sedimentary ridges with evidence of contiguous kilometer-scale, elongate-mounded shape composed of parallel-subparallel reflections, which are interpreted as sediment drifts (Fig. 3A). Their internal configuration is characterized by continuous, aggradational and progradational, low to high amplitude reflections, which are concave downward at the drift crests (Fig. 3A). The drifts are named as West-Wild drift, Wild drift, and Wilkins Drift, and exhibit thicknesses of 1-2.5 km (assuming velocity=2500 m/s) average lengths of 50–100 km, and average widths of 30–50 km (Figs. 1, 3). They extend downslope towards the NW, perpendicular to the margin of Mac. Robertson Land. Among the drifts, asymmetric channels are recognized in the seismic profile and bathymetry map (Figs. 1, 3). High-amplitude reflections suggest some erosional channeling (Figs. 3A, 4) that represents a strong impedance contrast to the underlying homogenous reflections in SU1. The cross sectional form of the drifts varies from V-shaped to U-shaped and they are strongly asymmetrical, especially at channel bends (Fig. 3A).

4.2. A shifting depocenter

Isopach (thickness) maps are produced for the three units SU1-SU3 based on the interpreted key seismic horizons of U1-U3 and seafloor. The map for the earliest deposited unit, SU1, shows that the main depocenter was located directly in front of the Prydz Bay coast. The maximum sediment thickness is up to 3500 ms (Fig. 5A). SU2 shows a prominent sedimentary wedge composed of MTDs and clinoforms on the slope of Mac. Roberson Land and becomes thinner toward the deep ocean, as observed on both seismic profiles and isopach map (Figs. 2, 3, 4, 5B). The focus of SU3 sediment deposition shifted northwestwards, away from the area offshore of Prydz Bay and towards Mac. Robertson Land. Here, estimated sediment thickness of this unit reaches more than 3000 ms (Fig. 5C). The new depocenter of this unit is composed of three large drifts (Figs. 3A, 5C).

4.3. Chronological framework

We correlate the lower unconformity U2 to the base of upper unit III in ODP Site 1166, where diatoms and pollen were sampled in the sand-dominated deposits and were assigned an age of about

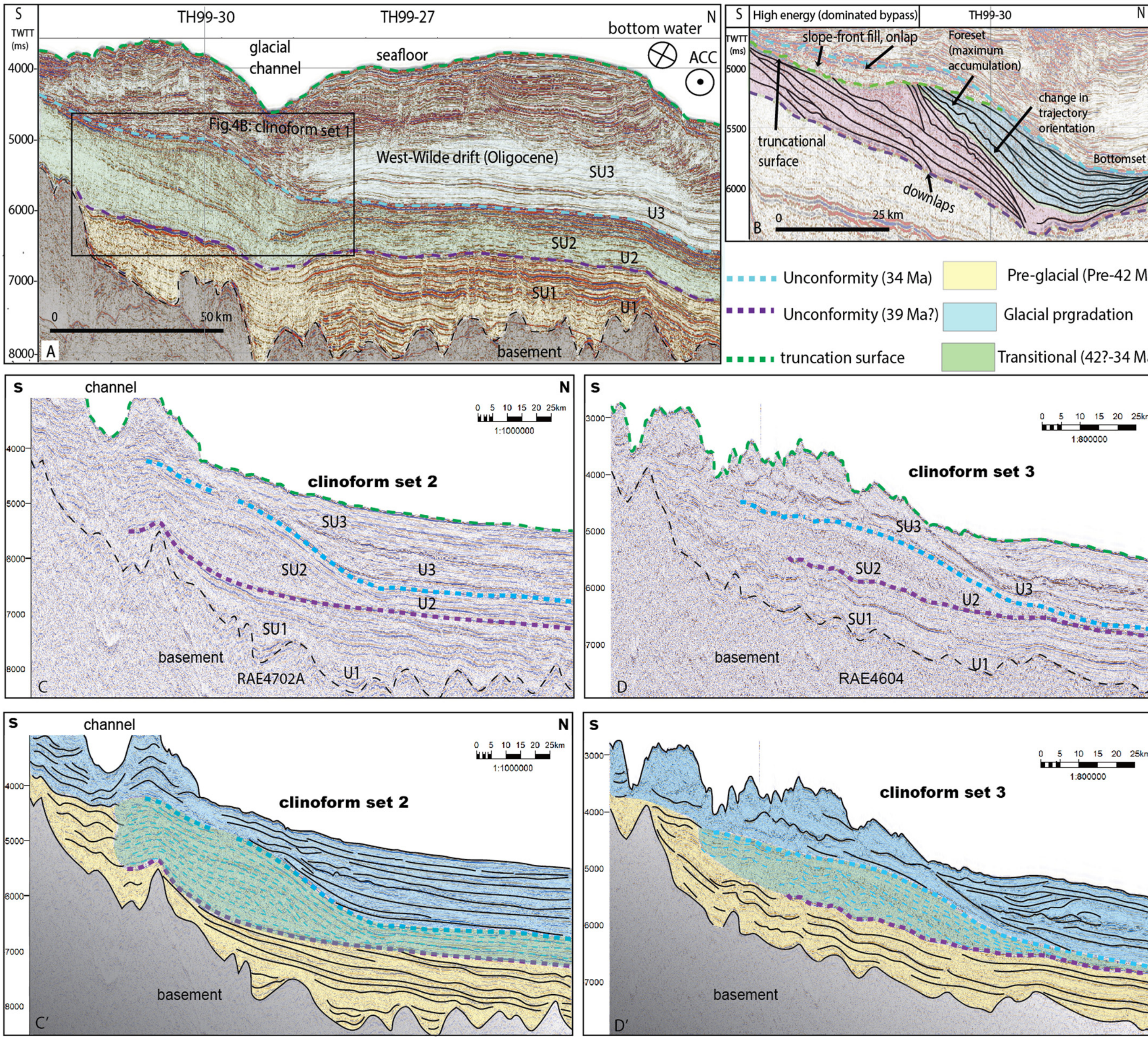

Fig. 4. More examples of clinoform sets, labeled as 1, 2 and 3 preserved on the Mac. Robertson Land margin. They show similar geometry and thin toward the basin. For locations see Fig. 1.

39 Ma (Fig. 2). During the same period, the presence of a layer with a high concentration of ice-rafted debris (IRD) dated to ~36 Ma on Kerguelen Plateau (ODP Site 748, ~1200 km north of Prydz Bay; Breza and Wise, 1992) is evidence of significant iceberg calving. This supports the interpretation of marine-terminating glacial advances in this region during the late Eocene, a time when ice has been suggested to have grounded on the continental shelf in Prydz Bay intermittently (Shipboard Scientific Party 2001).

Drilling at sites 1167 and 1165 (Fig. 1) terminated above the upper key unconformity of U3 in strata that are no older than early Miocene (Shipboard Scientific Party, 2001), thus providing a minimum age constraint to be pre-early Miocene. There are distinct changes of seismic reflection characteristics and implied process stratigraphy above and below this unconformity (Figs. 2, 3). The succession above exhibits incised canyons, deep water sediment drifts, and deep water-slope channel-levee systems. On this basis, we interpret the upper key unconformity U3 as marking the E-O boundary, which also corresponds to the reflector P1 of Kuvaas and Leitchenkov (1992). In our study, we suggest the succession between the lower (U2) and upper key unconformities (U3) was deposited between ~39 Ma and 34 Ma as a transitional phase to a glacially-dominated regime. An unusually thick and prominent transitional unit (SU2) composed of mega-MTDs and clinoforms off the Mac. Robertson Land margin has been well preserved, allowing a detailed interpretation of the non-glacial to glacial transition. We interpret the SU1 and SU3 intervals are representing preglacial and full glacial phases, respectively, and the depositional records in the seismic profiles provide crucial evidence of ocean circulation changes.

Interpretation of the seismic units and discussion The margins at Prydz Bay and Mac. Robertson Land regions have a thick (ca. 8 km) (Cooper et al., 1991) Cenozoic sedimentary succession that contains evidence for EAIS dynamics during the transition from a non-glacial to glacially controlled environment. We suggest that three successive sedimentary process regimes dominated on the mar-

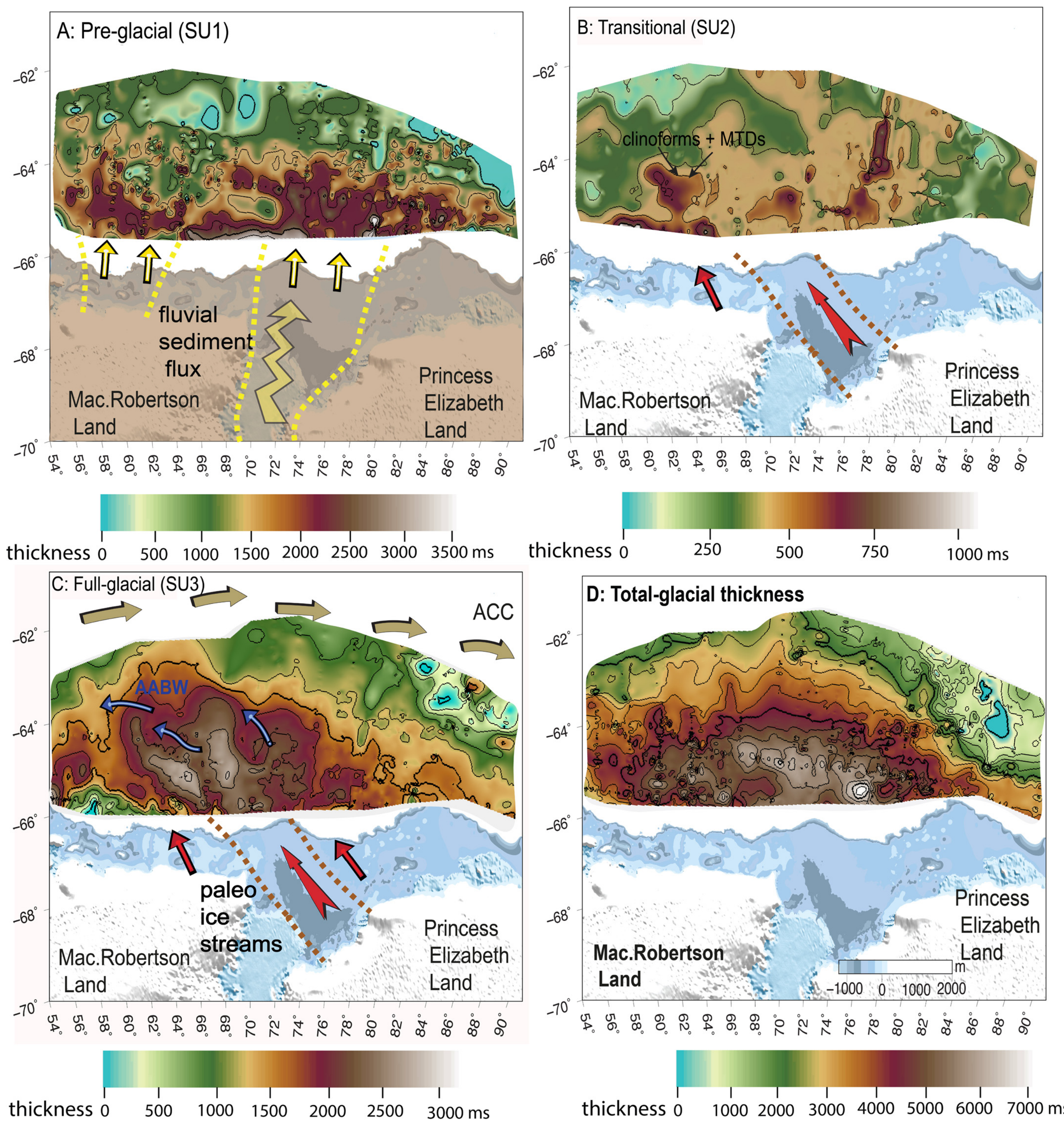

Fig. 5. A, B, C isopach maps of the strata within the preglacial phase, transitional phase and full glacial phase, respectively; D represents total sediment thickness. Schematic representation of the major sediment delivery pathways, depocenters and inferred ocean-circulation patterns. The yellow arrows represent fluvial transport dominated in the preglacial phase, the red arrows indicate the glacial transport, the blue arrows represent Antarctic Bottom Water, the blue arrows represent Antarctic Bottom Water (AABW).

gin at different stages in its development (Fig. 6): 1) fluvio-deltaic sediment delivery dominated the landscape during the preglacial phase; 2) during the transition, glacier-derived sediments were delivered by marine-terminating glaciers that began to carve troughs across the continental shelf and transferred onto the continental slope, generating glacigenic MTDs. Later in the transition stage turbidity currents became the main process transporting glacimarine sediments downslope to form well-developed slope clinforms. 3) in the glacially-controlled stage continued downslope sediment supply from turbidity currents was redistributed by newly established lower-slope contour currents that created a series of large contourite drifts to form the new depocenter. In present study, we mainly focus on the processes in the transitional and full glacial phases

4.4. Glacially-driven margin reorganization in the transitional phase

The transitional depocenter filled by mega-MTDs and prograding margin clinoforms was located in front of Mac. Robertson Land

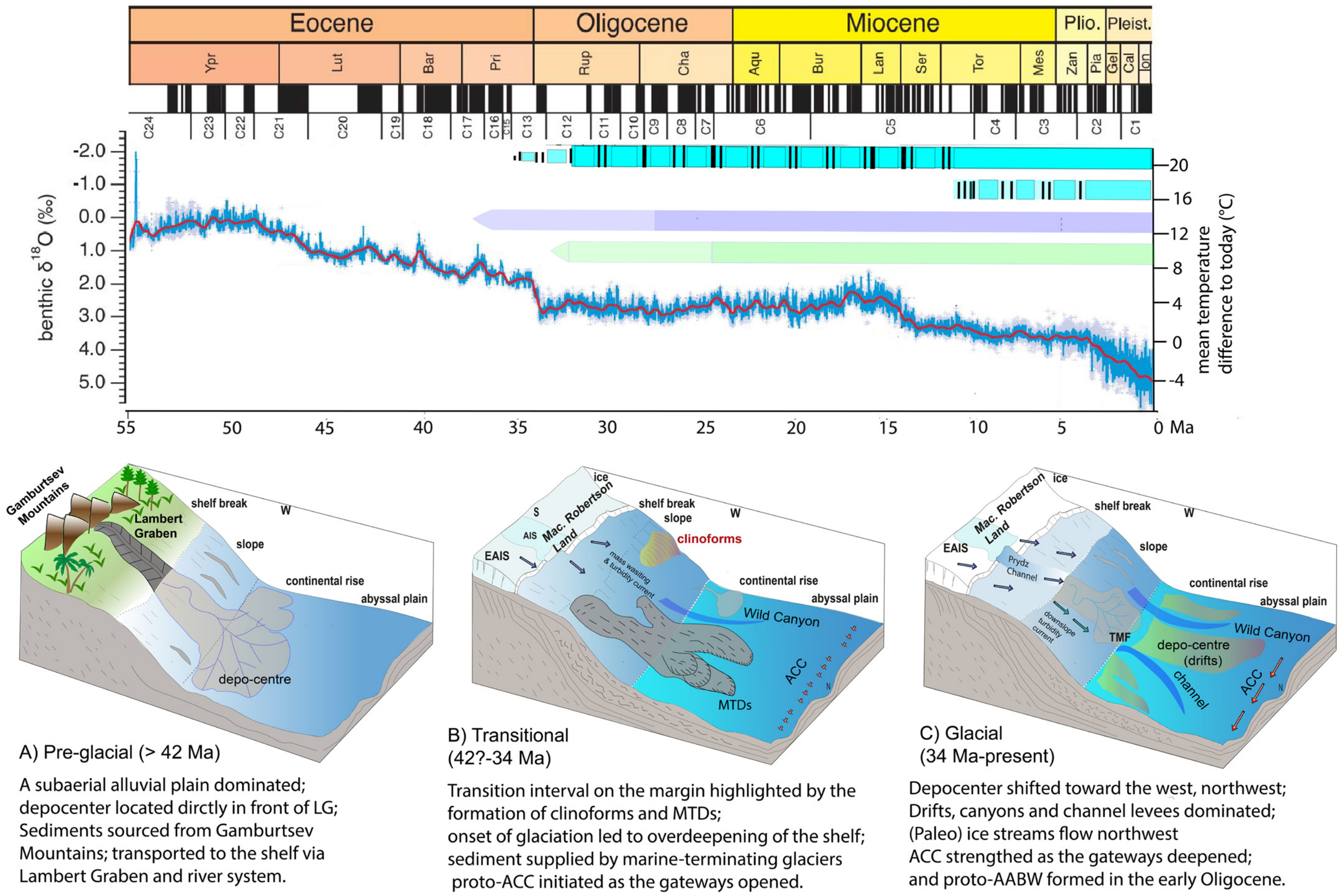

Fig. 6. Schematic summary of the sedimentary systems during the pre-glacial, transitional and full-glacial phases of margin development. The benthic oxygen isotope record was from Zachos et al. (2008).

and now can be seen to contain critical information for evaluating the onset of glaciation and early glacial dynamics in Antarctica in the late Eocene.

4.4.1. Glacial sediment loading caused shelf-edge instability and MTD generation

The MTD-fields that developed on the continental slope during the early transitional phase, according to our shelf-to-slope well tie correlation, are linked and broadly coeval with strongly regressive glacio-fluvial, sandy braid-plain deposits at ODP Site 1166 on the shelf. The MTDs are interpreted to result from shelf-edge instability, probably caused by rapid accumulation of thick outwash deposits in the Prydz Bay outer shelf and shelf-break zone. This led to large-scale shelf-edge collapse, feeding MTDs down onto the continental slope and base-of slope areas (Figs. 3B, C). We suggest that these mega-MTDs record early advances of the regional ice sheet building across the shelf. Subsequently, glaciofluvial environments in and around Prydz Bay gave way to glacial environments. These deposits attest to a variety of processes, ranging from small-scale mass wasting on the shelf to slope instability and slides covering thousands of square kilometers, a feature fairly typical of early glacial discharge in high sediment-accumulation areas (Nelson et al., 2011).

Our results are consistent with the study of Strand et al. (2003), who interpreted the coarse-grained sandstones cored in upper Unit III as alluvial plain or delta deposits. They recognized and interpreted the coarse-grained character of Unit III, containing a mix of rounded and angular grain shapes, as a glacial signature, suggesting that glaciers advanced to the coast in Prydz Bay even in the middle-late Eocene. The rounded coarse grains likely resulted from braided river and subaqueous delta processes in glacio-fluvial outwash, but the associated angular grains may have originated from fracturing by basal shear during glacier advance across the earlier outwash deposits. High sediment accumulation rates in some grounding zone and pro-glacial settings (Powell, 1990; Larter and Cunningham, 1993) combined with the occurrence of IRD in Southern Ocean sediments of similar age are consistent with the interpretation that glacial outwash formed an important component of Unit III at Site 1166. Analogous thick and widespread deposits resembling this unit and interpreted as pro-glacial fluvial outwash and subaqueous proglacial fans have been described in Algeria from deposits of the Ordovician glaciation and in Saudi Arabia from deposits of early Permian glaciations (Melvin and Sprague, 2006; Hirst, 2012).

4.4.2. Clinoform building marks healing of the collapsed slope and intensification of glacial influence

Following the phase of major shelf-edge instability and emplacement of the mega-MTDs, well-preserved clinoforms developed on the Mac. Robertson Land slope (Figs. 3, 4, 5B). Seismic horizons defining the prograding slope clinoforms have been traced back across the shelf, where pre-Miocene sediments were drilled (Figs. 3, 4). The local nature of the sets of clinoforms and their steepness suggest that they contain both mud and sand-rich material. Our shelf-to-slope correlation suggests that the clinoforms developed in the late transitional succession were generated at times close to, but before the E-O boundary (Fig. 2). The clinoform sets record the healing of the collapsed slope, reestablishment of margin accretion and the passage of downslope-directed turbidity currents fed by glaciers that repeatedly advanced and retreated over the narrow shelf (Figs. 4, 5, 6).

The clinoforms are a normal hallmark of prograding margins (Patruno and Helland-Hansen, 2018), but similar slope clinoforms have not been described elsewhere on the Antarctic margins during the transitional phase. We hypothesize that their stratigraphy is the result of forward accretion of the continental slope during periods of intense, gravity-driven downslope transport. The clinoforms would have been fed and sustained by high sediment flux from glacial troughs on the nearby shelf of Mac. Roberson Land (Figs. 4, 5). Clinoforms of this large scale originate by build-out of a prism of sediment from the slope, and subsequent gradual progradation of this sedimentary wedge by progressive extension of a sub-horizontal, subaqueous topset platform that presumably controlled by the base of strong along-slope current and continuously feeds a deep water slope (Figs. 3, 4A, B)

Keeping their different widths in mind, the Prydz Bay shelf and ODP Site 1166 serve as a useful analogue to the late Eocene Mac. Robertson Land shelf. The narrower and steeper margin off Mac. Robertson Land, with less space for storage of sediment on the shelf, allowed a greater proportion of the regional sediment supply to reach the deep water clinoform slope (Figs. 2, 5B). Hence, a narrow fluvial outwash plain passed seaward to an even narrower marine shelf over which coastal and marine terminating glaciers repeatedly advanced and retreated, delivering a high sediment flux to the continental slope. Retreat phases saw braided alluvium deposited on a shelf that was gradually being inundated by the ocean; the subsequent advance phases deformed and homogenized the earlier sands as the ice re-advanced to the shelf edge. Passchier et al. (2017) provide a well-resolved near-field record of Antarctic continental ice growth, temperature and weathering changes during the Eocene-Oligocene transition. They confirmed the presence of ephemeral mountain glaciers on East Antarctica during the late Eocene between 35.9 and 34.4 Ma and documented the stepwise climate cooling of the Antarctic hinterland from 34.4 Ma as the ice sheet advanced towards the edges of the continent during the Eocene-Oligocene precursor interval. Rapid erosion of soft sediments and substantial export of both bedload and suspended sediment by marine terminating glacier advances resulted in their redistribution in marine environments, producing significant accreting clinoforms, as has also been observed on the Alaskan and Greenland margins (Overeem et al., 2017).

Beyond the glacier front on the shelf there would have been ice-contact fans and their associated braid plains, or ice-contact gilbert-type deltas. We expect these features to have built out especially during glacial stillstands and retreats, and to have been subsequently buried by marine muds; marine mudstones overlying the early outwash and glacial deposits at Site 1166 indicate marine transgression, which is an expected consequence of growth of a large ice sheet due to the glacial isostatic adjustment (ice loading and gravitational attraction of ocean water towards the ice sheet) (Stocchi et al., 2013). We thus further hypothesize that the transitional period described in the current study, aided by glacial erosion below the advancing ice-sheet at times, may have been enhanced by postglacial subsidence. The first development of a continental ice sheet can be expected to have eroded very large volumes of soft sediment as it advanced across the shelf. This would have resulted in high sediment delivery to the continental slope, promoted and triggered instability in the first instance and subsequently provided the sediment supply to build the clinoforms.

Most clinoforms are formed during either highstand or falling-stage/lowstand conditions, where sediment supply is expected to outpace the rate of relative sea-level rise (Patruno et al., 2015). This period between Late Eocene and Early Oligocene is known to have been associated with a relative global sea-level fall of approximately 105 m (Katz et al., 2008). Regional tectonic subsidence rates were modest in comparison to the rates of glacial erosion and deposition in the Prydz Bay region (ten Brink and Schneider, 1995). However, Stocchi et al. (2013) found that the shelf areas around East Antarctica first shoaled as upper mantle material upwelled and a peripheral forebulge developed. The inner shelf subsequently subsided as lithosphere flexure extended outwards from the ice-sheet margins. Consequently, the coasts of East Antarctica experienced a progressive relative sea-level rise, which may also have affected the clinoforms development. To summarize, we suggest that key controls on the thickness, gradient and toplap truncation of the Mac. Robertson Land slope clinoform system was seal level rise and high sediment supply related to the presence and activity of vigorous marine terminating glaciers during the E-O Transition.

4.5. From Greenhouse to Icehouse: a change to vigorous ocean current circulation

The location of the Prydz Bay depocenter shifted permanently towards the northwest from the preglacial to full glacial stage (Fig. 5). The new depocenter in the full glacial stage was dominated by northwest-elongated sediment drifts at the base-of-slope (West-Wild, Wild and Wilkins drifts) in the Early Oligocene (Fig. 3A). Contourite deposition began in the basinal areas at ∼34 Ma (Figs. 2–3), implying an increased ocean current vigor from the beginning of Oligocene. The drifts are characterized by mounded morphology with parallel-subparallel low-amplitude reflections occurring in strata interpreted as being of Oligocene and Miocene age (Figs. 3, 5, 6). The sharp cooling at this time may also have resulted in increased sea ice formation and thus deep water production, such dense deep water would flow downslope, becoming focused into channels, until it reached the abyssal plains. High amplitude reflections highlight the past positions of submarine channels of the continental slope (e.g. Wild Canyon and other channels that were conduits for turbidity currents transporting glacially-derived sediments to the deep ocean, Figs. 3, 5C). Lower amplitude reflections extend laterally from the paleo-channels into the drift mounds (Fig. 3A) suggesting that much of the drift sediment was derived from downslope turbidity currents, and redistributed by W-flowing bottom currents (Figs. 3, 5C). The slope turbidity currents were confined by channels, which exhibit low sinuosity and migrated towards the NW through time (Figs. 3A, 6C). The largest and oldest trunk channel, 'Wild Canyon', was host to turbidity currents enhanced during glaciation (Figs. 3A). The channels are interpreted to have formed in a setting dominated by erosional density driven flows that transported glacially-derived sediment to deeper parts of the basin.

With deposition focused along persistent current pathways, contourite drifts have developed into large sedimentary bodies (e.g., thickness of 100–1000 m and lateral distribution of 10–100 km) that hold long-term records of oceanic circulation and climate. In combination with sediment thicknesses and migration patterns (Figs. 3A, 5), we suggest that the deep W-paleocurrent flow (confined by channels) involved a major part of the water mass column, representing a far more vigorous regime than the preglacial regime. We propose that this current comprised the proto-Antarctic Bottom Water (p-AABW) that initially formed during stepwise cooling in the Early Oligocene, in response to the establishment of perennial sea ice at the Prydz Bay and Mac. Robertson Land margins.

4.6. Implications

In the light of the above stratigraphic analysis for the onset of change to glacial conditions, we note that there is also considerable evidence that this E-O climate change was associated with a very significant change in deep-ocean circulation. At about 37.5 Ma, circum-equatorial surface water was directed southwards in the Indian Ocean via the Agulhas Current, as a result of the constricting Tethys Gateway (Diekmann et al., 2004). This current is a possible source of the moisture thought to be a critical element in maintaining a large mid-Cenozoic Antarctic ice sheet (Zachos et al., 2008). During the full glacial phase, the Antarctic ice sheet itself became a driver of climate and ocean changes. Enhanced katabatic wind circulation resulted in increased wind shear/curl and increased circum-Antarctic-upwelling. The wind-driven ACC likely intensified during the opening of the Southern Ocean gateways in the early Oligocene, amplifying the global cooling that had started earlier (Stickley et al., 2004; Hochmuth et al., 2020; Sauermilch et al., 2021), though decline of pCO2 is the major driving mechanism of cooling (DeConto and Pollard, 2003; Lauretano et al., 2021). The above changes have had an important impact on sediment-accumulation patterns. The redistribution of sediments that resulted in development of the drifts and new depocenter in the early Oligocene is evidence of the p-AABW (Fig. 5). However, the origin and long-term significance of the current system has remained somewhat unclear. Future work with new ocean drilling is needed to further understand the complex water masses and their interaction with Antarctic ice sheet dynamics during the greenhouse to icehouse transition. The contourite drifts and clinoforms described have the potential to yield long-term records of Southern Ocean paleoclimatic and paleoceanographic change spanning this critical period.

5. Conclusions

Integration of an extensive seismic reflection dataset with sparse control from scientific ocean drilling results reveals how the change from Eocene greenhouse to Oligocene icehouse impacted the paleo-environments and the process stratigraphy of the Antarctic margin. The newly defined Eocene-Oligocene stratigraphic transition is characterized by an abrupt increase in sediment supply, resulting in mega-MTD fields on the slope followed by well-ordered prograding, slope clinoforms around the Prydz Bay and Mac. Roberson Land region. The mega-MTDs are attributed mainly to sedimentary loading and collapse of the shelf edge at the time of the first advances of the regional ice sheet entirely across the shelf. The clinoform building marks intensification of glacial sediment flux on to the margin and sea level rise during the transitional phase. Together, these features provide strong evidence of the first signals of the glacial onset in the late Eocene. Above the E-O boundary, the change to full glacial conditions is recognized by an obvious shift of the offshore depocenter and enhanced contourite deposition towards the west and northwest, indicating change to more vigorous ocean circulation changes. Enhancement of the ACC and emplacement of a proto-AABW likely paved the way for further oceanographic feedbacks that interacted with Antarctic glaciation through the late Cenozoic.

CRediT authorship contribution statement

Xiaoxia Huang: Conceptualization, methodology, producing figures and drafting the manuscript. **Ronald Steel**, **Rob Larter:** analyzing and discussing the results, editing the manuscript (multiple times).

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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References

Arndt, J.E., Schenke, H.W., Jakobsson, M., Nitsche, F.O., Buys, G., Goleby, B., et al., Wigley, R., 2013. The International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0—A new bathymetric compilation covering circum-Antarctic waters. Geophys. Res. Lett. 40 (12), 3111–3117. https://doi.org/10.1002/grl.50413.

Barron, J.A., Baldauf, J.G., Barrera, E., Caulet, J.P., Huber, B.T., Keating, B.H., et al., Wei, W., 1991. Biochronologic and magnetochronologic synthesis of Leg 119 sediments from the Kerguelen Plateau and Prydz Bay, Antarctica. In: Barron, J., Larsen, B., et al. (Eds.), Proc. ODP. In: Sci. Results, vol. 119, pp. 813–847.

Breza, J.R., Wise Jr, S.W., 1992. 12. Lower Oligocene Ice-Rafted Debris on the Kerguelen Plateau: Evidence for East Antarctic Continental Glaciation.

Carter, A., Riley, T.R., Hillenbrand, C.D., Rittner, M., 2017. Widespread Antarctic glaciation during the late Eocene. Earth Planet. Sci. Lett. 458, 49–57. https://doi.org/10.1016/j.epsl.2016.10.045.

Cooper, A.K., O'Brien, P.E., 2004. Leg 188 synthesis: transitions in the glacial history of the Prydz Bay region, East Antarctica, from ODP drilling. In: Proceedings of the Ocean Drilling Program: Scientific Results, vol. 188, pp. 1–42.

Cooper, A.K., Barrett, P.J., Hinz, K., Traube, V., Letichenkov, G., Stagg, H.M., 1991. Cenozoic prograding sequences of the Antarctic continental margin: a record of glacio-eustatic and tectonic events. Mar. Geol. 102 (1–4), 175–213.

Coxall, H.K., Wilson, P.A., Pälike, H., Lear, C.H., Backman, J., 2005. Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean. Nature 433 (7021), 53–57. https://doi.org/10.1038/nature03135.

DeConto, R.M., Pollard, D., 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2. Nature 421 (6920), 245–249. https://doi.org/10.1038/nature01290.

Diekmann, B., Kuhn, G., Gersonde, R., Mackensen, A., 2004. Middle Eocene to early Miocene environmental changes in the sub-Antarctic Southern Ocean: evidence from biogenic and terrigenous depositional patterns at ODP Site 1090. Glob. Planet. Change 40 (3–4), 295–313. https://doi.org/10.1016/j.gloplacha.2003.09.001.

Eagles, G., Jokat, W., 2014. Tectonic reconstructions for paleobathymetry in Drake Passage. Tectonophysics 611, 28–50. https://doi.org/10.1016/j.tecto.2013.11.021.

Ehrmann, W.U., Mackensen, A., 1992. Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time. Palaeogeogr. Palaeoclimatol. Palaeoecol. 93 (1–2), 85–112. https://doi.org/10.1016/0031-0182(92)90185-8.

Escutia, C., De Santis, L., Donda, F., Dunbar, R.B., Cooper, A.K., Brancolini, G., Eittreim, S.L., 2005. Cenozoic ice sheet history from East Antarctic Wilkes Land continental margin sediments. Glob. Planet. Change 45 (1–3), 51–81. https://doi.org/10.1016/j.gloplacha.2004.09.010.

Ferraccioli, F., Finn, C.A., Jordan, T.A., Bell, R.E., Anderson, L.M., Damaske, D., 2011. East Antarctic rifting triggers uplift of the Gamburtsev Mountains. Nature 479 (7373), 388–392. https://doi.org/10.1038/nature10566.

Florindo, F., Bohaty, S.M., Erwin, P.S., Richter, C., Roberts, A.P., Whalen, P.A., Whitehead, J.M., 2003. Magnetobiostratigraphic chronology and palaeoenvironmental history of Cenozoic sequences from ODP sites 1165 and 1166, Prydz Bay, Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 198 (1–2), 69–100.

Fretwell, P., Pritchard, H.D., Vaughan, D.G., Bamber, J.L., Barrand, N.E., Bell, R., Bianchi, C., Bingham, R.G., Blankenship, D.D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A.J., Corr, H.F.J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J.A., Hindmarsh, R.C.A., Holmlund, P., Holt, J.W., Jacobel, R.W., Jenkins, A., Jokat, W., Jordan, T., King, E.C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K.A., Leitchenkov, G., Leuschen, C., Luyendyk, B.P., Matsuoka, K., Mouginot, J., Nitsche, F.O., Nogi, Y., Nost, O.A., Popov, S.V., Rignot, E., Rippin, D.M., Rivera, A., Roberts, J., Ross, N., Siegert, M.J., Smith, A.M., Steinhage, D., Studinger, M., Sun, B., Tinto, B.K., Welch, B.C., Wilson, D., Young, D.A., Xiangbin, C., Zirizzotti, A., 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. Cryosphere 7, 375–393. https://doi.org/10.5194/tc-7-375-2013.

Galeotti, S., DeConto, R., Naish, T., Stocchi, P., Florindo, F., Pagani, M., Zachos, J.C., 2016. Antarctic Ice Sheet variability across the Eocene-Oligocene boundary climate transition. Science 352 (6281), 76–80. https://doi.org/10.1126/science.aab0669.

Gohl, K., Uenzelmann-Neben, G., Larter, R.D., Hillenbrand, C.D., Hochmuth, K., Kalberg, T., Nitsche, F.O., 2013. Seismic stratigraphic record of the Amundsen Sea Embayment shelf from pre-glacial to recent times: evidence for a dynamic West Antarctic ice sheet. Mar. Geol. 344, 115–131. https://doi.org/10.1016/j.margeo.2013.06.011.

Goldner, A., Herold, N., Huber, M., 2014. Antarctic glaciation caused ocean circulation changes at the Eocene–Oligocene transition. Nature 511 (7511), 574–577. https://doi.org/10.1038/nature13597.

Gulick, S.P., Shevenell, A.E., Montelli, A., Fernandez, R., Smith, C., Warny, S., Blankenship, D.D., 2017. Initiation and long-term instability of the East Antarctic Ice Sheet. Nature 552 (7684), 225–229. https://doi.org/10.1038/nature25026.

Hambrey, M.J., Ehrmann, W., Larsen, B., 1991. Cenozoic glacial record of the Prydz Bay continental shelf, East Antarctica. In: Barron, J., Larsen, B. (Eds.), Proc. ODP Sci. Results. 119. Ocean Drilling Program. College Station, TX, pp. 77–132. 119, 77–132.

Hernández-Molina, F.J., Paterlini, M., Violante, R., Marshall, P., de Isasi, M., Somoza, L., Rebesco, M., 2009. Contourite depositional system on the Argentine Slope: an exceptional record of the influence of Antarctic water masses. Geology 37 (6), 507–510. https://doi.org/10.1130/G25578A.1.

Hill, D.J., Haywood, A.M., Valdes, P.J., Francis, J.E., Lunt, D.J., Wade, B.S., Bowman, V.C., 2013. Paleogeographic controls on the onset of the Antarctic circumpolar current. Geophys. Res. Lett. 40 (19), 5199–5204. https://doi.org/10.1002/grl.50941.

Hirst, J.P.P., 2012. Ordovician proglacial sediments in Algeria: insights into the controls on hydrocarbon reservoirs in the In Amenas field, Illizi Basin. Geol. Soc. (Lond.) Spec. Publ. 368 (1), 319–353. https://doi.org/10.1144/SP368.17.

Hochmuth, K., Gohl, K., Leitchenkov, G., Sauermilch, I., Whittaker, J.M., Uenzelmann-Neben, G., De Santis, L., 2020. The evolving paleobathymetry of the circum-Antarctic Southern Ocean since 34 Ma: a key to understanding past cryosphere-ocean developments. Geochem. Geophys. Geosyst. 21 (8), e2020GC009122. https://doi.org/10.1029/2020GC009122.

Huang, X., Jokat, W., 2016. Middle Miocene to present sediment transport and deposits in the Southeastern Weddell Sea, Antarctica. Glob. Planet. Change 139, 211–225. https://doi.org/10.1016/j.gloplacha.2016.03.002.

Huang, X., Bernhardt, A., De Santis, L., Wu, S., Leitchenkov, G., Harris, P., O'Brien, P., 2020. Depositional and erosional signatures in sedimentary successions on the continental slope and rise off Prydz Bay, East Antarctica–implications for Pliocene paleoclimate. Mar. Geol. 430, 106339. https://doi.org/10.1016/j.margeo.2020.106339.

Huang, X., Wu, S., De Santis, L., Wang, G., Hernández-Molina, F.J., 2022. Deep water sedimentary processes in the Enderby Basin (East Antarctic margin) during the Cenozoic. Basin Res. https://doi.org/10.1111/bre.12690.

Jamieson, S.S.R., Hulton, N.R.J., Sugden, D.E., Payne, A.J., Taylor, J., 2005. Cenozoic landscape evolution of the Lambert basin, East Antarctica: the relative role of rivers and ice sheets. Glob. Planet. Change 45 (1–3), 35–49. https://doi.org/10.1016/j.gloplacha.2004.09.015.

Katz, M.E., Miller, K.G., Wright, J.D., Wade, B.S., Browning, J.V., Cramer, B.S., Rosenthal, Y., 2008. Stepwise transition from the Eocene greenhouse to the Oligocene icehouse. Nat. Geosci. 1 (5), 329–334. https://doi.org/10.1038/ngeo179.

Kuvaas, B., Leitchenkov, G., 1992. Glaciomarine turbidite and current controlled deposits in Prydz Bay, Antarctica. Mar. Geol. 108 (3–4), 365–381. https://doi.org/10.1016/0025-3227(92)90205-V.

Larter, R.D., Cunningham, A.P., 1993. The depositional pattern and distribution of glacial-interglacial sequences on the Antarctic Peninsula Pacific margin. Mar. Geol. 109 (3–4), 203–219. https://doi.org/10.1016/0025-3227(93)90061-Y.

Lauretano, V., Kennedy-Asser, A.T., Korasidis, V.A., Wallace, M.W., Valdes, P.J., Lunt, D.J., Naafs, B.D.A., 2021. Eocene to Oligocene terrestrial Southern Hemisphere cooling caused by declining pCO2. Nat. Geosci. 14 (9), 659–664. https://doi.org/10.1038/s41561-021-00788-z.

Lear, C.H., Bailey, T.R., Pearson, P.N., Coxall, H.K., Rosenthal, Y., 2008. Cooling and ice growth across the Eocene-Oligocene transition. Geology 36 (3), 251–254. https://doi.org/10.1130/G24584A.1.

Livermore, R., Nankivell, A., Eagles, G., Morris, P., 2005. Paleogene opening of Drake passage. Earth Planet. Sci. Lett. 236 (1–2), 459–470. https://doi.org/10.1016/j.epsl.2005.03.027.

López-Quirós, A., Escutia, C., Etourneau, J., Rodríguez-Tovar, F.J., Roignant, S., Lobo, F.J., Sicre, M.A., 2021. Eocene-Oligocene paleoenvironmental changes in the South Orkney Microcontinent (Antarctica) linked to the opening of Powell Basin. Glob. Planet. Change 204, 103581. https://doi.org/10.1016/j.gloplacha.2021.103581.

Maldonado, A., Carlos Balanyá, J., Barnolas, A., Galindo-Zaldívar, J., Hernández, J., Jabaloy, A., et al., Viseras, C., 2000. Tectonics of an extinct ridge-transform intersection, Drake Passage (Antarctica). Mar. Geophys. Res. 21 (1), 43–68.

Melvin, J., Sprague, R.A., 2006. Advances in Arabian stratigraphy: origin and stratigraphic architecture of glaciogenic sediments in Permian-Carboniferous lower Unayzah sandstones, eastern central Saudi Arabia. GeoArabia 11 (4), 105–152. https://doi.org/10.2113/geoarabia1104105.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., et al., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. Science 310 (5752), 1293–1298. https://doi.org/10.1126/science.1116412.

Nelson, C.H., Escutia, C., Damuth, J.E., Twichell, D.C., 2011. Interplay of mass-transport and turbidite-system deposits in different active tectonic and passive continental margin settings: external and local controlling factors. Sediment. Geol. 96, 39–66.

O'Brien, P.E., Cooper, A.K., Richter, C., et al., 2001. Proc. ODP, Init. Repts., vol. 188. College Station, TX (Ocean DrillingProgram).

Ohshima, K.I., Fukamachi, Y., Williams, G.D., Nihashi, S., Roquet, F., Kitade, Y., Wakatsuchi, M., 2013. Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. Nat. Geosci. 6 (3), 235–240. https://doi.org/10.1038/ngeo1738.

Orsi, A.H., Johnson, G.C., Bullister, J.L., 1999. Circulation, mixing, and production of Antarctic Bottom Water. Prog. Oceanogr. 43 (1), 55–109. https://doi.org/10.1016/S0079-6611(99)00004-X.

Overeem, I., Hudson, B.D., Syvitski, J.P., Mikkelsen, A.B., Hasholt, B., Van Den Broeke, M.R., Noël, B.P.Y., Morlighem, M., 2017. Substantial export of suspended sediment to the global oceans from glacial erosion in Greenland. Nat. Geosci. 10 (11), 859–863. https://doi.org/10.1038/ngeo3046.

Party, S.S., 2001. Leg 188 summary: Prydz Bay–Cooperation Sea, Antarctica. In: O'Brien, P.E., Cooper, A.K., Richter, C. (Eds.), Proc. ODP Init. Repts., vol. 188, pp. 1–65.

Passchier, S., Ciarletta, D.J., Miriagos, T.E., Bijl, P.K., Bohaty, S.M., 2017. An Antarctic stratigraphic record of stepwise ice growth through the Eocene-Oligocene transition. Geol. Soc. Am. Bull. 129 (3–4), 318–330. https://doi.org/10.1130/B31482.1.

Patruno, S., Helland-Hansen, W., 2018. Clinoforms and clinoform systems: review and dynamic classification scheme for shorelines, sub-aqueous deltas, shelf edges and continental margins. Earth-Sci. Rev. 185, 202–233. https://doi.org/10.1016/j.earscirev.2018.05.016.

Patruno, S., Hampson, G.J., Jackson, C.A., 2015. Quantitative characterisation of deltaic and subaqueous clinoforms. Earth-Sci. Rev. 142, 79–119. https://doi.org/10.1016/j.earscirev.2015.01.004.

Pérez, L.F., Martos, Y.M., García, M., Weber, M.E., Raymo, M.E., Williams, T., et al., Zheng, X., 2021. Miocene to present oceanographic variability in the Scotia Sea and Antarctic ice sheets dynamics: Insight from revised seismic-stratigraphy following IODP Expedition 382. Earth Planet. Sci. Lett. 553, 116657. https://doi.org/10.1016/j.epsl.2020.116657.

Powell, R.D., 1990. Glacimarine processes at grounding-line fans and their growth to ice-contact deltas. Geol. Soc. (Lond.) Spec. Publ. 53 (1), 53–73. https://doi.org/10.1144/GSL.SP.1990.053.01.03.

Rose, K.C., Ferraccioli, F., Jamieson, S.S., Bell, R.E., Corr, H., Creyts, T.T., Damaske, D., 2013. Early east Antarctic Ice Sheet growth recorded in the landscape of the Gamburtsev Subglacial Mountains. Earth Planet. Sci. Lett. 375, 1–12. https://doi.org/10.1016/j.epsl.2013.03.053.

Sauermilch, I., Whittaker, J.M., Klocker, A., Munday, D.R., Hochmuth, K., Bijl, P.K., LaCasce, J.H., 2021. Gateway-driven weakening of ocean gyres leads to Southern Ocean cooling. Nat. Commun. 12 (1), 1–8. https://doi.org/10.1038/s41467-021-26658-1.

Stickley, C.E., Brinkhuis, H., Schellenberg, S.A., Sluijs, A., Röhl, U., Fuller, M., Grauert, M., Huber, M., Warnaar, J., Williams, G.L., 2004. Timing and nature of the deepening of the Tasmanian Gateway. Paleoceanography 19 (4). https://doi.org/10.1029/2004PA001022.

Stocchi, P., Escutia, C., Houben, A.J., Vermeersen, B.L., Bijl, P.K., Brinkhuis, H., Yamane, M., 2013. Relative sea-level rise around East Antarctica during Oligocene glaciation. Nat. Geosci. 6 (5), 380–384. https://doi.org/10.1038/ngeo1783.

Strand, K., Passchier, S., Näsi, J., 2003. Implications of quartz grain microtextures for onset Eocene/Oligocene glaciation in Prydz Bay, ODP Site 1166, Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 198 (1–2), 101–111. https://doi.org/10.1016/S0031-0182(03)00396-1.

ten Brink, U.S., Schneider, C., 1995. Glacial morphology and depositional sequences of the Antarctic continental shelf. Geology 23 (7), 580–584. https://doi.org/10.1130/0091-7613(1995)023<0580:GMADSO>2.3.CO;2.

Tripati, A., Backman, J., Elderfield, H., Ferretti, P., 2005. Eocene bipolar glaciation associated with global carbon cycle changes. Nature 436 (7049), 341–346. https://doi.org/10.1038/nature03874.

Uenzelmann-Neben, G., Gohl, K., Hochmuth, K., Salzmann, U., Larter, R.D., Hillenbrand, C.D., Klages, J.P., 2022. Deep water inflow slowed offshore expansion of the West Antarctic Ice Sheet at the Eocene-Oligocene transition. Commun. Earth Environ. 3 (1), 1–10.

Zachos, J.C., Dickens, G.R., Zeebe, R.E., 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature 451 (7176), 279–283. https://doi.org/10.1038/nature06588.