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Depositional and erosional signatures in sedimentary successions on the continental slope and rise off Prydz Bay, East Antarctica– implications for Pliocene paleoclimate

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ABSTRACT

The Prydz Bay region of Antarctica is the immediate recipient of ice and sediments transported by the Lambert Glacier, the single largest outflow from the East Antarctic Ice Sheet. The continental slope and rise provide records covering multiple glacial cycles and containing paleoclimatic information. Marine geological and geophysical data collected from the continental shelf and adjacent slope of Prydz Bay, Antarctica, including seismic reflection data, bathymetry, and core records from ODP drilling sites, reveal the history of glacial sediment transport and deposition since the early Pliocene times. Seismic facies are interpreted in terms of episodes of slope progradation, contourite, turbidite, trough-mouth fan, and mass transport deposition. Two seismic units with estimated age of early to late Pliocene and late Pliocene to recent have been analyzed in detail for the area immediately offshore the Lambert Glacier and Prydz Bay and the adjacent Mac. Robertson margin. The upper slope is dominated by episodic mass transport deposits, many of which accumulated to form a trough mouth fan since Early Pliocene times. The trough mouth fan contrasts with the adjacent steep (4–6°) continental slope of the Mac. Robertson margin, where glacigenic sediments have been transported down slope as high-velocity turbidity currents via submarine channels. The distal region exhibits evidence for contrasting effects of high-energy, traction-dominated versus lower-energy, fallout-dominated suspension flows. The counter-clockwise Coriolis force modifies the erosion and deposition patterns of turbidity currents creating an asymmetric channel-levee architecture. Since the early Pliocene, turbidite sedimentation surpassed the amount of sediment reworked and transported by westward-flowing contour currents along the base of slope. On the continental rise, contourites and sediment waves were deposited in response to enhanced bottom-water formation, which is consistent with climatic cooling since late Pliocene times. This study, based on existing seismic reflection and ODP data, highlights the need for a future scientific ocean drilling proposal on the Prydz Bay continental slope and rise in order to more accurately determine the timing of the important events that have influenced the evolution of this margin.

1. Introduction

The Pliocene epoch (5.333–2.588 Ma) was characterized by significant cooling of high latitude regions (Kleiven et al., 2002; Ravelo et al., 2004) punctuated by short time intervals when the climate was substantially warmer than it is at the present (Dowsett et al., 1996; Thompson and Fleming, 1996; Fedorov et al., 2013). The behavior of the Antarctic ice sheet under these conditions can be reconstructed from proxy data and Ice-Rafted Debris (IRD) records from ODP sites scattered around the Antarctic margins (Passchier et al., 2003; Williams et al., 2010). Based on these data, significant warming at high latitudes is thought to have caused retreat of the Pliocene ice sheets, which in

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turn affected the extent of sea ice and raised global sea level (Harwood and Webb, 1998; Raymo et al., 2006, 2011; Naish et al., 2009; Patterson et al., 2014; Cook et al., 2013). It has been argued that the late Pliocene was a period of exceptionally high climate sensitivity (Tripati et al., 2009; Pagani et al., 2011). However, the contribution of the Antarctic versus the Northern Hemisphere ice sheets to Pliocene global sea level change is still difficult to deconvolve from the deep-sea isotope record. Detailed timing and spatial pattern of Antarctic ice sheet retreat is incompletely constrained by drill-core data because of the wide spacing of drill sites and the numerous downhole hiatuses that limit spatial and temporal resolution (Sugden and Denton, 2004; Haywood et al., 2009).

The existing seismic reflection and drill core data provide a long-term record of Antarctic glaciation and its intimate relationships with global climatic and oceanographic change (De Santis et al., 2003; O'Brien et al., 2007; Nitsche et al., 2000, 2007; Cooper et al., 2008; Larter and Barker, 2009; Bart and De Santis, 2012; Escutia et al., 2009, 2019; Gohl et al., 2013; Huang et al., 2014; Huang and Jokat, 2016; Larter et al., 2019). Ice sheet advances to the shelf edge during glacial maxima saw the deposition of large volumes of unconsolidated sediments as gravity flows, including mass-transport deposits (MTDs) and prograding wedges or trough mouth fans (TMFs), cone- or fan-shaped deposits of terrigenous sediments located seaward of glacially formed shelf-crossing submarine troughs (Laberg and Vorren, 1995). TMF deposits probably consist of remobilized and remolded sediment gravity flow deposits similar in composition to the proximal till sediments found on the shelf (Gales et al., 2019) and, thus, form archives of glacially transported sediments which are intimately related to the history of glaciation (Vorren and Laberg, 1997; O'Cofaigh et al., 2003). TMFs have been described on both Arctic and Antarctic margins (Vorren et al., 1989; Bart et al., 1999; Cooper and O'Brien, 2004; O'Cofaigh et al., 2005; Gulick et al., 2017; Montelli et al., 2017). In the Antarctica, Early Pliocene TMF growth is also reported from the Weddell Sea (Bart et al., 1999) and Antarctic Peninsula Pacific margins (Larter et al., 1997; Hernández-Molina et al., 2017).

At the middle to low latitudes, large submarine canyons and gully networks are globally critical links between the coast, shelf and abyssal plains (Covault and Graham, 2010). Two main processes for channel formation are retrograde slope failures and erosion by turbidity currents (Pratson and Coakley, 1996). Submarine channels confined to the continental slope and may represent an incipient stage of channel development, due to retrograde slope failure, of which only some will evolve to eventually extend up-slope to become shelf-incising channels, which are the largest channel features (Harris and Whiteway, 2011; Gales et al., 2013; Amblas et al., 2018; O'Brien et al., 2020). At the polar regions, submarine channels are on average twice the size of non-polar canyons and this is attributed to large sediment volumes delivered to margins by glacial processes as compared with fluvial processes (Harris et al., 2014). Erosional V-shaped canyons and gullies can indent the continental shelf and uppermost slope and can transition into U-shaped submarine channels with overbank deposits or submarine fan along the lower continental slope and rise (e.g., Covault, 2011). Sediment deposition has dominated over erosion around the Antarctic margin (Escutia et al., 2005; Harris and Whiteway, 2011; Huang and Jokat, 2016), resulting in a semi-continuous continental rise that encircles the continent (Harris et al., 2014). Channel systems associated with TMFs, mass-transport deposits, contourites and sediment waves can provide valuable archives to study the dynamics of past ice sheets.

Turbidity currents transport large volumes of sediment from the shelf and slope to the deep-seafloor and are important to the construction of continental margins. The initiation process of turbidity currents probably involves turbulent mixing and microscale convection, as in the production of hyperpycnal flows at river mouths (Parsons et al., 2007) or from the remobilization of upper slope sediments form channels on the continental slope which, upon reaching the continental rise, overspill the channels to generate overbank complexes (Pratson and Coakley, 1996; Covault, 2011). Coriolis forces are known to influence large-scale gravity currents (Komar and Inman, 1970), and become dominant at high latitudes so that deposition is biased strongly to one side of channels. The deflection of the turbidity current by Coriolis forces leads to an asymmetry between levee bank heights. The right-hand-side channel levee is consistently higher in the Northern Hemisphere and the left-hand-side channel levee is higher in the Southern Hemisphere, looking downstream (Carter and Carter, 1988; Bruhn and Walker, 1997; Wood and Mize-Spansky, 2009; Wells and Cossu, 2013). On the continental rise, sediments either can settle forming submarine fan or be picked up by contour currents to be deposited further downstream as contourite drifts or sediment waves (Stow and Lovell, 1979). On the Antarctic margin, the development of some contourite drifts favored by the formation of Antarctic Bottom Water (AABW) and the delivery of large volumes of sediment by fast-flowing ice streams to the outer shelf during glacial periods (Hernández-Molina et al., 2017). The sediment drifts contain climatic and oceanographic information valuable for the reconstruction of Neogene Antarctic glacial history (Rebesco et al., 1996; Barker and Camerlenghi, 2002; Amblas et al., 2006; Hillenbrand et al., 2008).

Prydz Bay (Fig. 1A) is ideal to study the links between sedimentary patterns and Pliocene glacial evolution because its margin was dominated by glacial processes that led to the development of diverse Pliocene-aged depositional and erosional signatures including submarine channels, TMFs, and contourites on the continental slope and rise. However, most of comprehensive studies regarding seismic well tie correlation is mainly focused on the continental shelf of Prydz Bay, which was the target of ODP Leg 119 and its pre-site surveying (Mizukoshi et al., 1986; Leitchenkov et al., 1994; Cooper et al., 1991; O'Brien and Harris, 1996). A decade later, ODP leg 188 (Sites 1165–1167) (Shipboard Scientific Party, 2001; Cooper and O'Brien, 2004; Whitehead et al., 2006; O'Brien et al., 2007) revisited the region with a focus on understanding the glacial history and paleoceanography of Prydz Bay. The shelf and Prydz Channel Fan have been studied intensively, based on these ODP drilling sites, bathymetry, and seismic data (Passchier et al., 2003; Passchier, 2011; Cooper and O'Brien, 2004; O'Brien et al., 2016). However, few studies have concentrated on the seismic sequence of the slope and rise off Prydz Bay, and the distribution and overall volume of glacially-influenced sediment deposition in this region remain uncertain.

Kuvaas and Leitchenkov (1992) identified a number of sediment ridges and attributed their formation to the influence of combined turbidity and bottom currents. They focused on discussing the possible onset time of these current activities, which were suggested to have occurred: a) at the Eocene/Oligocene boundary when the Amery Ice Shelf first reached the shelf break, which enhanced slope deposition and increased turbidites, followed by; b) a phase of enhanced contour currents at around the Oligocene/Miocene boundary corresponding to the widening and deepening of the Drake Passage. However, due to absence of information from the later drilling (ODP Leg 188), Kuvaas and Leitchenkov (1992) correlated ODP Leg 119 drilling sites (Barron et al., 1991) from the continental shelf to the rise and compared them with the seismic reflection pattern of glaciomarine sequences in the Weddell Sea. Such distant correlation and comparison leaves a large gap in the seismic stratigraphic record resulting in poor age control of sedimentary features on the continental rise off the Prydz Bay. In addition, the seismic expression of the Pliocene regime is outside the scope of Kuvaas and Leitchenkov (1992). No subsequent seismic studies have concentrated on interpreting seismic sequences in terms of Pliocene depositional patterns along the continental slope and rise of Prydz Bay. The extent of Pliocene glaciomarine sedimentary deposition on the slope and rise thus remains uncertain.

In this study, we use regional bathymetry, borehole information and over 7000 km of seismic reflection profiles to identify submarine geomorphic features and their erosional and depositional signatures to provide an improved understanding of glacially-influenced sedimentary

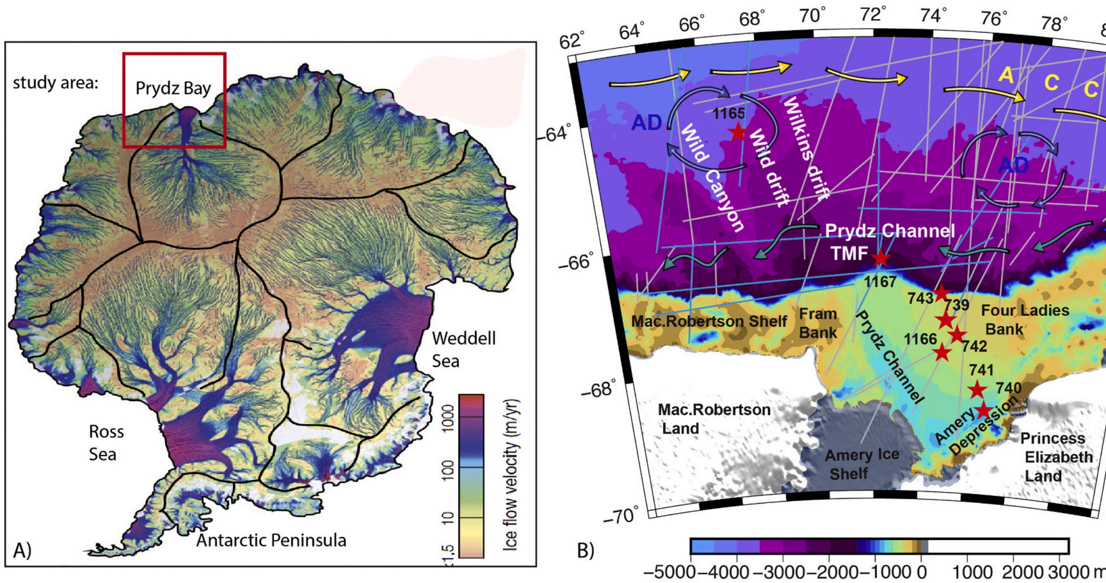


Fig. 1. A) Ice flow of the Antarctica (Rignot et al., 2011) and 1B) bathymetric map of the Prydz Bay region (IBSCO, Arndt et al., 2013). Blue lines are the revisited seismic lines in this study. Red stars are the locations of the sites visited during ODP legs 119 and 188. Yellow arrows represent the direction of Antarctic Circumpolar Current (ACC). The green arrows represent the Antarctic Costal Current, close to shelf edge. The two clockwise-rotating gyres shown by blue arrows represent the Antarctic Divergence (AD). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

system and paleoclimatic changes during the Pliocene. In detail, we focus on the Pliocene to recent seismic reflection patterns along two study areas in the broader Prydz Bay region: Mac. Robertson Land and Prydz Bay slope and rise (Fig. 1A and B) which feature submarine channels located on the continental rise between drift deposits, in particular the Wild Canyon, a set of episodic large mass transport deposits (MTDs), a TMF, contourites, and sediment waves. We aim to establish the relationships between these sedimentary structures and external factors such as shelf morphology, slope gradient, turbidites, contour-current regime and glacial dynamics.

2. Geological and oceanographic setting

Prydz Bay lies at the seaward end of the Lambert Graben, a deep basement structure onshore that extends about 500 km inland (Stagg et al., 2004; Leitchenkov et al., 2014; O'Brien et al., 2016). The offshore area is underlain by the Prydz Bay sedimentary basin, which contains as much as 12 km of sediment (Cooper et al., 1991). The Lambert Graben is developed largely in Precambrian metamorphic basement and likely formed by rifting in Permian-Triassic and Jurassic to Cretaceous times, with possible tectonic reactivation later in the Cretaceous (Hambrey et al., 1991; Ferraccioli et al., 2011; Leitchenkov et al., 2020). The broad pattern of ice and sediment movement in the region is controlled by the graben, which is now covered by the Lambert Glacier–Amery Ice Shelf ice drainage system. It drains ~16% of the area of the East Antarctic Ice Sheet or 10% of all Antarctic ice outflow (Fricker et al., 2001).

Modern ocean circulation in the Prydz Bay region is complex (Fig. 1B). The deep-water movements on the continental slope and rise are attributed to four large-scale ocean systems: 1) the Antarctic Coastal Current, moving west near the shelf edge; 2) the Antarctic Divergence, producing cyclonic gyres over the slope and 3) the rising of warm, intermediate Circumpolar Deep Water (CDW) and Antarctic surface water flow eastward within ACC, while Antarctic Bottom Water (AABW) flows downslope and northward beneath the CDW; 4) and the Antarctic Circumpolar Current, moving east over the outer rise and beyond (Harris and O'Brien, 1998; Cooper and O'Brien, 2004). In addition to Weddell and Ross seas and in the Adelie Land polynyas (Fahrbach et al., 1994; Orsi et al., 1999; Williams et al., 2010, 2016; Huang et al., 2017), Polynyas offshore from Cape Darnley, just west of Prydz Bay, have been shown to be a significant site of bottom water formation (Ohshima et al., 2013).

3. Data and materials

3.1. Seismic reflection data

The data presented include gridded single-beam bathymetry from the International Bathymetric Chart of the Southern Ocean (IBSCO) (Arndt et al., 2013) and multichannel seismic reflection data, focusing on the sea-floor morphology and glacial sedimentary processes on the Prydz Bay continental margin. 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 including six surveys (BMR33, TH89, TH99, RAE 52, GA228, GA229) acquired by Australian, Russian and Japanese Antarctic programs. Approximately 7000 km of seismic data of fair to good quality were recorded. All of the data have been processed following standard procedures to CMP stack and time migrated. The northern ends of most lines terminated at 66° S, in water depths of 2500–3000 m. The seismic lines were downloaded from SDLS (http://sdls.ogs.trieste.it) in SEG-Y format and their associated navigation data were used to import them into a unified georeferenced system in Petrel E&P software platform for further interpretation. We reinterpreted approximately 7000 km of multichannel seismic data on the Prydz Bay continental margin. All the vertical scales for seismic profiles shown in the study are two-way travel time. Reflections in the data set are tied to the stratigraphy generated from drill cores of ODP legs 119 and 188.

3.2. Seismic-well tie and age estimation

Studies of the stratigraphy of ODP legs 119 and 188 regarding seismic-well tie correlation are mainly focused on the continental shelf of Prydz Bay (Barron et al., 1991; O'Brien et al., 2004; Cooper and O'Brien, 2004). An early Pliocene and younger glacial section was

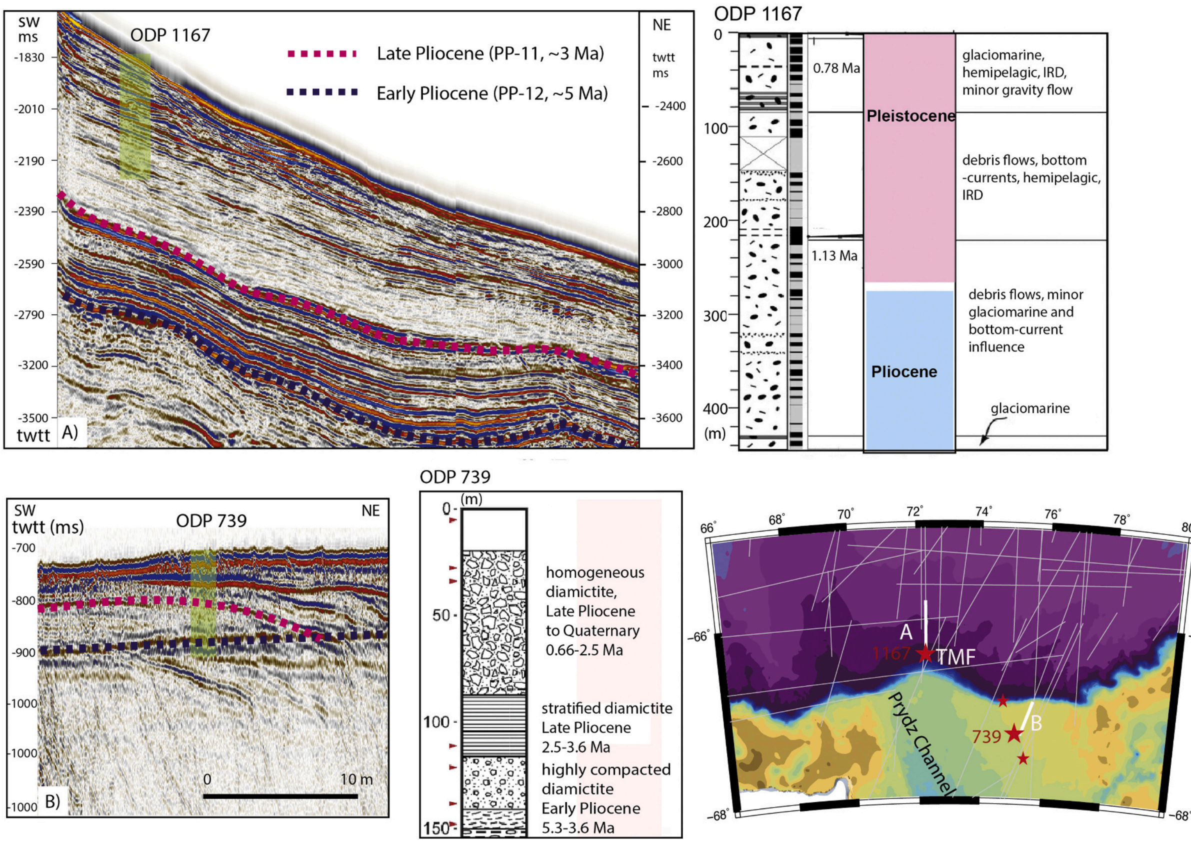


Fig. 2. The locations of the ODP site 1167 and 739, as well as the seismic lines, which cross the two sites. Profile A (TH99-32): crossed ODP site 1167 from the Prydz Channel Fan; Profile B (BMR33-27): crossed ODP site 739 from the shelf. The core logs are modified after Passchier et al., 2003) and Barron et al., 1991). Red stars mark the ODP sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

encountered at sites 739 (0–24 mbsf, total depth: 486 mbsf) and 1166 (0–135 mbsf, total depth: 450 mbsf) on the continental shelf (Shipboard Scientific Party, 2001). The section was interpreted to represent the advances and retreats of the continental ice sheet (O'Brien et al., 2004; Shipboard Scientific Party, 2001). Barron et al. (1991) and O'Brien et al. (2007) tied the PP-12 reflector to ODP Site 739 (at 105.9–130 mbsf) to infer that the reflector, and hence the onset of the Prydz Channel and its TMF, are of early Pliocene age.

ODP site 1167 was drilled on the Prydz Channel TMF and it is also the first deep drill hole in an Antarctic TMF. The core provides an expanded view of Pleistocene glacial fluctuations over the past 1–2 0.58 Myr (Figs. 1, 2). Passchier et al., 2003) dated the sediment core using nannoplankton and strontium isotope chronology from a depth near 217 mbsf, which has an age of ~1.1 Ma. Drilling ended at 447 mbsf and did not reach the bottom of the fan, which is marked by reflector PP-12 with its suggested Early Pliocene age at the onset of the Prydz Channel Fan (O'Brien et al., 2004). Based on the above, we use the nomenclature PP-12 and PP-11 to represent the Early Pliocene (~5 Ma) and the Late Pliocene (~3 Ma), respectively, and tentatively correlate the two sequences lying above each of these reflectors to sedimentary features, in order to provide an age control over the slope and rise. PP-12 and PP-11 are both deeper than the base of the ODP Site 1167 on the continental slope. It is also challenging to definitively tie the drilling records between the shelf (ODP site 739), slope (ODP site 1167), and distal rise (ODP site 1165), because the sedimentary section thins between the sites (Cooper and O'Brien, 2004). The Pliocene section of ODP site 1165 is only about 50 m thick, which is below the resolution of existing seismic data. In general, the drill core data needed to correlate and constrain the seismic stratigraphy of the Pliocene section on the continental slope and rise are still lacking.

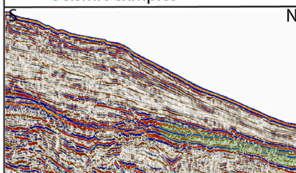
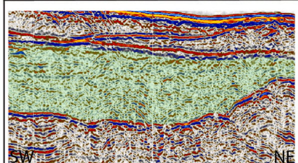
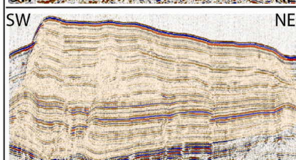
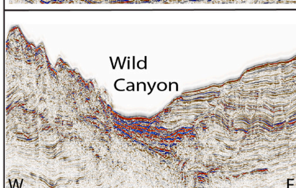
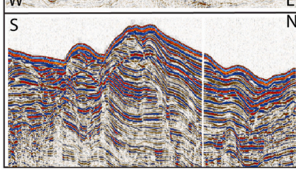
4. Results and interpretation

4.1. Prydz Bay margin vs Mac. Robertson Land margin

The bathymetric map of the Prydz Bay margin (Fig. 1) shows irregular relief on the upper continental rise resulting from a number of sediment mounds and intervening channels, especially offshore of the glacially eroded troughs on the shelf. Most of the channels appear to originate at the base of the continental slope and are difficult to observe in the current bathymetry due to its low resolution, but can be resolved in the 2D seismic data. A number of depositional and erosional features, such as channel-levees, MTDs, contourite drifts, and the TMF are recognizable along the Mac. Robertson Land and Prydz Bay margin on the basis of their distinct seismic expressions (Table 1, Fig. 3). The bathymetry of Prydz Bay is broadly similar to many other part of the Antarctic shelf, with an inwardly-deepening continental shelf approaching depths of 1000 m in the southwestern corner of the *bay. The* shelf extends over 250 km out to the shelf break (Figs. 1, 4A;Mackintosh et al., 2014*). In* the inner part of Prydz Bay is the Amery Depression, which descends generally to depths of about 800 m but contains deeper closed depressions of up to 1100 m water depth in the south-west (Fig. 1). Extending northwest from the Amery Depression to the shelf edge, the shelf is dominated by a 150 km-wide, S-N-trending, glacial shelf-crossing trough, with 700–800 m deep, the Prydz Channel. The channel is flanked by Fram Bank to the west and Four Ladies Bank to the east located in < 200 m water depth on the middle to outer shelf (Figs. 1, 3).

The continental slope off the western side of Prydz Bay is gentle and has a smooth morphology characterized by oceanward convex bathymetric contours whereas the slopes adjacent to the east and west are steeper and incised by numerous channels (Fig. 4A). The Mac.

Table 1
major seismic facies, their location and distribution are illustrated in Fig. 3.

Seismic exmples	Facies	Characteristics	Interpretation
	facies A: prograding slope facies (Figs. 3, 5)	stacked sequences of clinoform reflectors downlapping and intercalated with weakly stratified reflectors. Partly chaotic reflection is observed.	Tough-mouth fan (TMF) deposits composed by prograding seqeunces and mass-transport deposits (MTDs), formed due to glacial ice advances, which deliver sediment from the continent shelf to the slope.
	facies B: chaotic or transparent facies (Figs. 3, 6C)	irregular to hummocky, or chaotic, or transparent facies, lenticular or mounded geometry.	Similar to facie A, MTDs of facie B is the major component of TMF, formed by gravity flow during glacia maximum.
	facies C: mounded, weakly stratified facies (Figs. 3, 7C)	parallel or subparallel, continuous, low-to moderate-amplitude reflectors, gently undulating, forming asymmetric mounds	drift deposits, dominantly hemipelagic, formed by turbidity and bottom currents, modified by Coriolis effect as well.
	facies D: stratified cut-and-fill facies (Figs. 3, 8B)	packets of well-stratified, parallel to divergent reflectors (levees), truncated by channel-like features; Layered high amplitude reflection within channel (canyon infill).	Channel-levee complex. The mounded divergent and migrated wavy seismic facies can be explained as canyon levees consisting mainly of fine turbidits. Well-sorted, coarse-grained sediments generally fill channel talwegs. The channel infill generally shows a chaotic-opaque acoustic facies.
	facies E: discontinuous wavy seismic facies (Figs. 3, 9A)	show an asymmetrical morphology with a steeper, less well-layered, and shorter upslope flank; associated with discontinuous reflections and even truncated terminations gentle, well-layered, longer downslope flank.	sediment waves, were possibly formed and modified by both turbidity current and bottom current, which are coexist in the study region.

Robertson Land continental margin, located to the west of the Prydz Bay margin (O'Brien et al., 2016), has a relatively narrow continental shelf extending 70–80 km seaward of the present-day ice margin (Figs. 1, 3). The inner shelf contains some sub-basins with minor thicknesses of sedimentary fill (up to 200 m) deposited on rugged and partly exposed basement (Fig. 4B). Glacial incisions like the Nielsen Basin (Fig. 4B), are cut into the inner continental shelf (Harris and O'Brien, 1998). The incisions are largely filled with chaotic, draped and cross-stratified deposits (Fig. 4B). The basin fills are characterized by high amplitude reflection patterns. The morphology of the middle shelf is rather flat and the overlying sedimentary cover is about 400 m thick. The outer shelf shows a basin fill with up to 700–1000 m of sediments

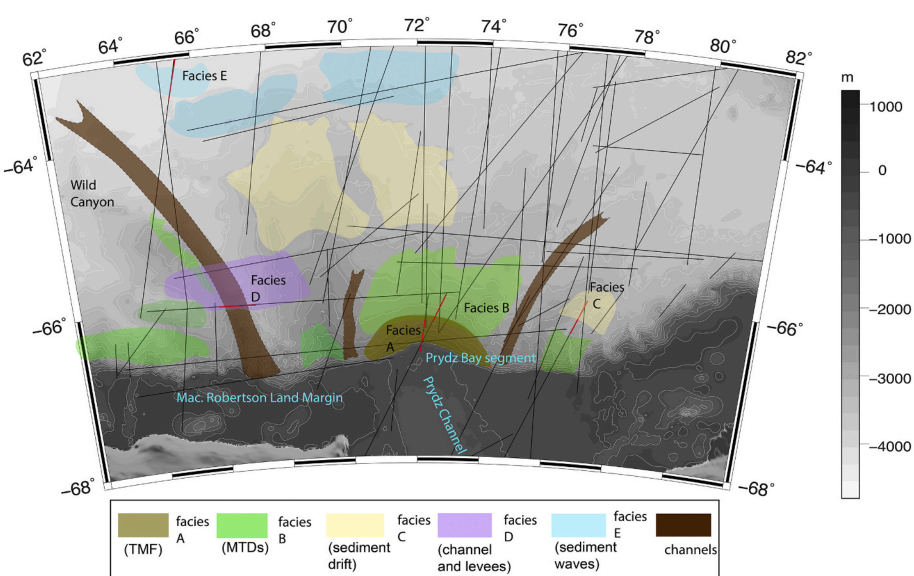


Fig. 3. Five key seismic facies distribution identified in the study region, the red lines represent the locations of the seismic examples shown in the Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

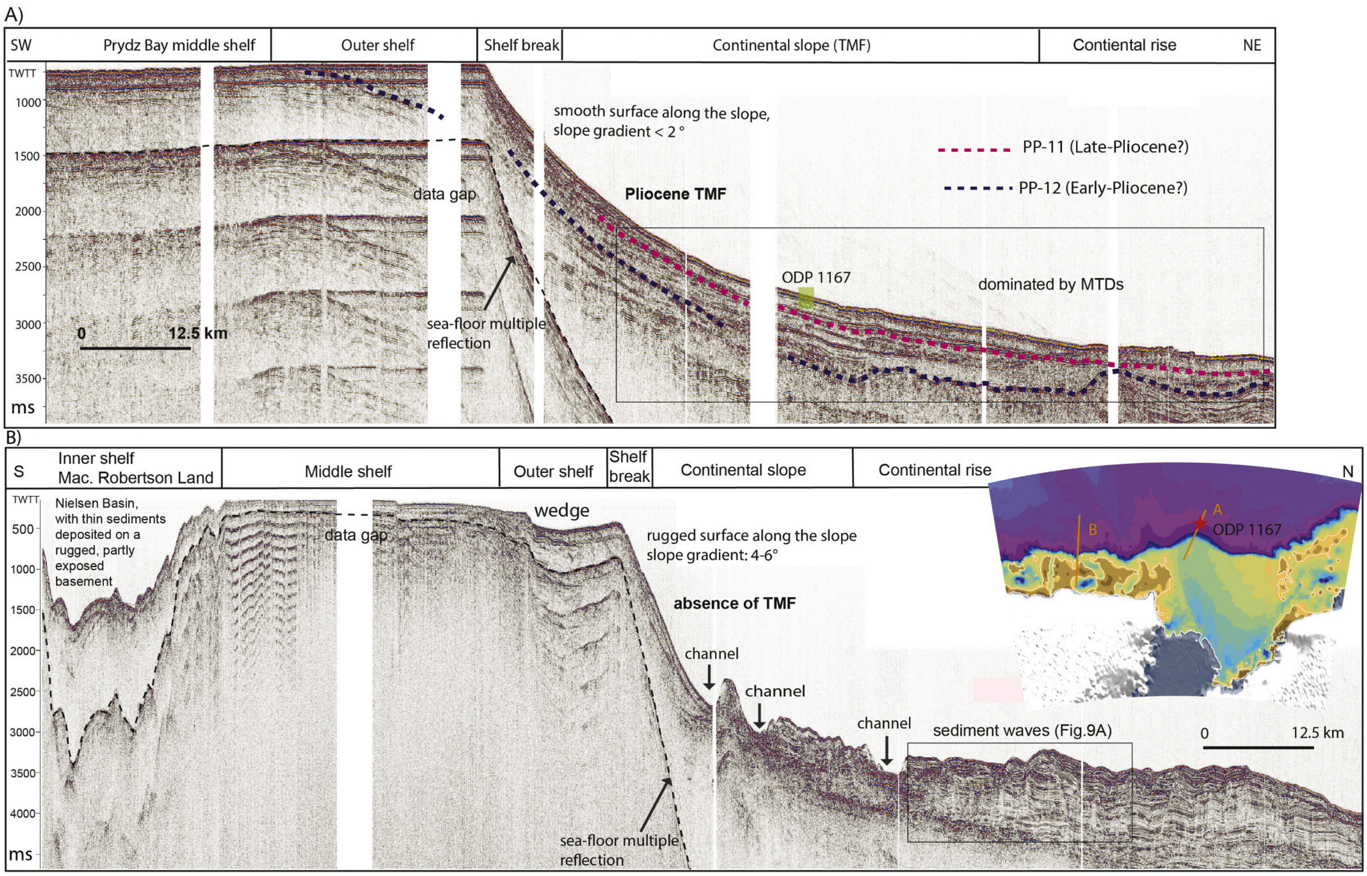


Fig. 4. The geomorphology of the Prydz Bay margin (A): BMR33-57, Mac. Robertson Land continental margin (B): BMR33-63.

that display complex sigmoid-oblique reflections, prograding near the shelf edge (Fig. 4B).

The Mac. Robertson margin segment (Fig. 3) displays a steep upper slope with gradients of 4–6° (from depth of 400 to 1800 m), extending 60–80 km outwards from the shelf break. A broad lower slope with shallower gradients (c. 0.4–1°, from depth of 1500 m to 2500 m) extends seawards (Fig. 4B). Limited deposition has occurred on the slope, which is instead dominated by a complex network of shelf/slope channels (Figs. 1, 4B). The lower slope to continental rise segment is overlain by sediments up to 1.5 km thick that exhibit discontinuous undulating reflectors and truncated terminations to the seabed, interpreted here as sediment waves, facies E (Fig. 4 B). Facies E are observed to occur widely on the lower continental slope and rise (Figs.3, 4B, Table 1).

4.2. TMF and MTDs along the Prydz Bay margin

The most prominent depositional feature of the terminal prograding wedge along the margin is the large sedimentary Fan located offshore from the mouth of Prydz Channel, previously identified by Kuvaas and Leitchenkov (1992) and by O'Brien et al. (2007) (Figs. 1, 5). The Prydz Channel TMF is 150 km wide and extends over 90 km out from the margin to a water depth of 2700 m (Fig. 5). It is identified by distinctive convex-seawards bathymetric contours located between 500 and 2500 m water depth (Fig. 1). The upper fan extends from the shelf break to about 1500 m water depth and is characterized by a slope gradient of about 0.8° along its central axis. The middle to lower fan, from about 1500 to 3000 m water depth, has an average gradient of 0.5° (Fig. 4A).

Facies A is characterized by prograding outer shelf–upper slope strata, interpreted as Prydz Channel Fan, which is located directly in front of the Prydz Channel, (Table 1, Fig. 3). In the seismic data, packages of reflectors in the Prydz Channel Fan show a sigmoidal geometry and extensive semi-continuous reflectors defining acoustically transparent packages (Fig. 5, Table 1). The upper and lower fan are dominated by mounded geometries and chaotic seismic signatures (Fig. 5A). The base of the TMF is marked by an unconformity, which is characterized by a distinct reflector with high amplitude, previously marked as PP-12 (O'Brien et al., 2007; Fig. 5A). The maximum thickness of the TMF is up to 700–800 m in its proximal reaches and thins to 100–300 m in its distal parts (Fig. 5 A, B). A series of acoustically transparent features with irregular surface topography and downslope elongation are interpreted as MTDs with varying widths, thicknesses and lengths. These features (Figs. 5, 6) make up the bulk of sediment volume on the lower TMF, and mark the area of its most recent active growth.

Seismic data reveal several widespread facies B, which are characterized by variable internal seismic architectures, dominated by acoustically transparent, partly hummocky, chaotic, contorted, semi-transparent, and discontinuous reflections and diffractions, which are interpreted as MTDs (Table 1, Figs. 6). MTDs located between the upper and mid slope, restricted to those areas in which the gradient of the upper 1000 m of the continental slope is < 1° in the study area (Fig. 6). Several features that we interpret as MTDs were identified at different stratigraphic levels within the 2000–3000 s TWTT thick Pliocene to Pleistocene sedimentary cover with irregular upper and lower surfaces (Fig. 6). On the seismic lines perpendicular to the continental margin, the MTDs appear within prograding sigmoidal/oblique reflections and semi-transparent lenses or opaque wedges (Figs. 5, 6). The individual bodies are mostly acoustically transparent and can be clearly identified on seismic reflection data. The bounding surfaces of the individual MTDs appear as sharp, continuous and strong reflectors (Fig. 6).

The MTDs are elongated, up to 50 km wide and 200 m (assuming

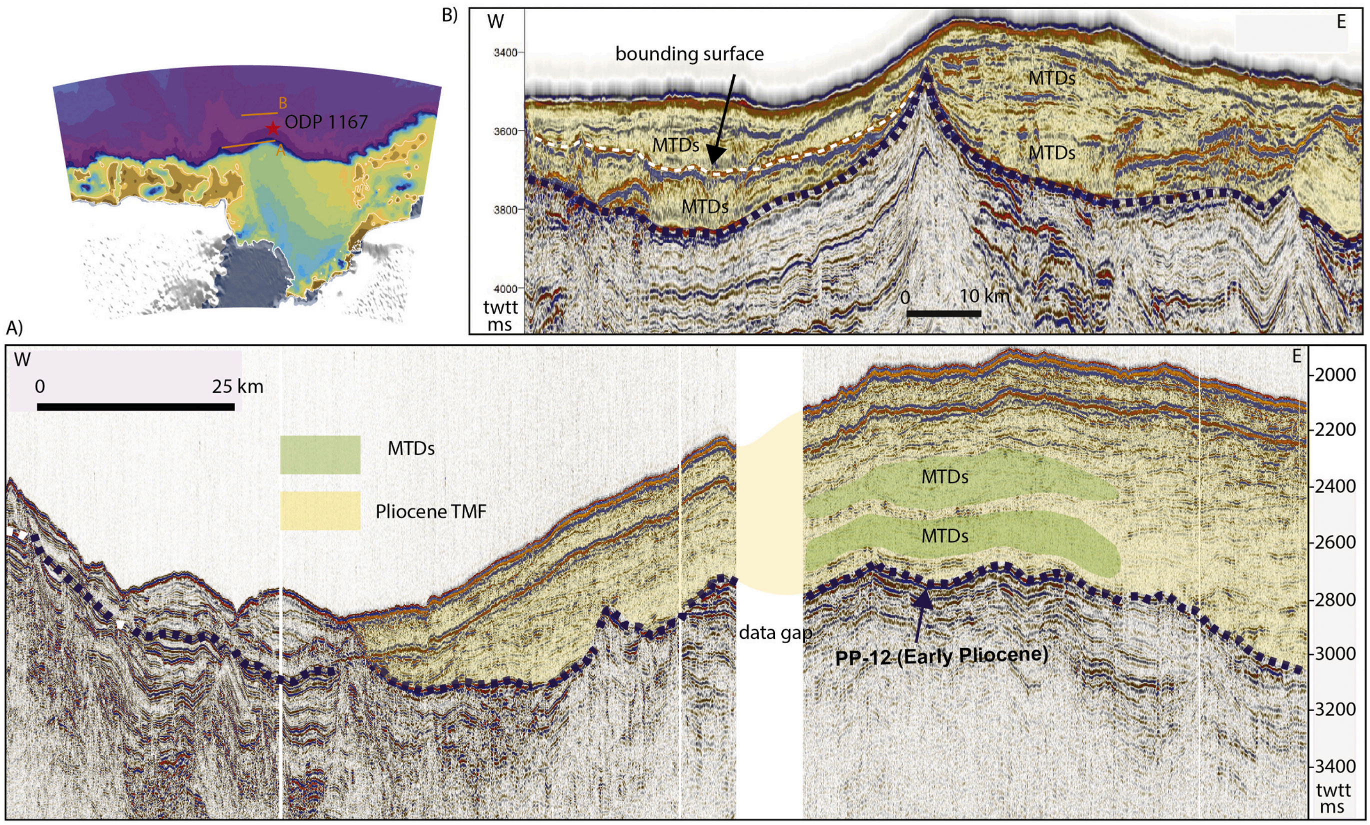


Fig. 5. The proximal (A: BMR33-11) and distal (B: TH99-30) parts of the Prydz Channel TMF, illustrated by seismic data, the star represents the ODP site 1167.

seismic-wave velocity in sediment: 1800 m/s, O'Brien et al., 2004) thick, and can be traced over 100 km downslope. They are characterized by abrupt lateral and downslope terminations and are internally transparent (Fig. 6). Some MTDs exhibit lens-shaped, internal chaotic reflections with relatively high-amplitude reflections at their base. The internal reflections are irregular and discontinuous, with interruptions over distances of several kilometers (Fig. 6). The coherent basal seismic reflectors of the individual MTDs (Fig. 6B, C) are interpreted as basal shear surfaces that acted as detachments during emplacement. These shear surfaces represent the planes above which downslope translation occurred.

4.3. Channel levee-drift system

Abrupt changes in sediment depositional pattern are observed to mark the lower slope termination of the TMF as shown in seismic expression (Fig. 6A). Reflection patterns shift abruptly downslope from facies B to facies C. The more distal part is characterized by flat and parallel reflectors lying seaward of a break in slope, which represents the toe of the prograding Prydz Channel Fan and the limit of facies B (Fig. 6A, Fig. 7A, Table 1). A 5–7 km-wide channel separates a sedimentary mound from the continental slope. Water depth in the channel is up to ca 3400 m (Fig. 7A). The slope deposits of the entire Pliocene sequence are dominated by MTDs, which shows chaotic reflections (thickness of 0.5 km, length of 80 km, Fig. 7A). The mound developed above the key reflector PP-11 on the continental rise has a constructional internal structure with apparent truncation on the SW-flank. Reflectors of facies B are parallel to subparallel and exhibit a high- to moderate-amplitude. The sedimentary mound is interpreted as a drift, or channel levee-drift system (Faugères et al., 1999). The channel levee-drift system is comprised probably of hemipelagic mud deposited by westward-flowing bottom currents and downslope turbidity current, and thus shows evidence for being molded or partially shaped by them. With deposition focused along persistent current pathways, the drift accumulated (thickness of 0.4 km and lateral extent of over 75 km; Fig. 7A), which may contain valuable records of oceanic climate and circulation.

Distinctive, elongated sediment ridges are developed above the unconformity PP-11 on the eastern side of the Prydz Channel Fan, (Fig. 7A, B, and C marked in light yellow). The ridges are characterized by mounded, asymmetric geometry with weakly stratified facies, which shows parallel or subparallel, continuous reflectors on the upper and lower continental rise. The internal reflectors are configurational and diverge into southwest-migrating lenticular units (Figs. 7A, B). This deposition pattern is characteristic of contourite drifts, produced by the westward-flowing bottom currents interacting with seafloor topography and sediment available for along-slope transport. Evidence of fault activity and the occurrence of widespread erosional features are linked with large-scale mass movements, such as slumps (Figs. 7B and C).

4.4. Wild Canyon along the Mac. Robertson Land margin

Submarine channels occur with a variety of widths and depths on the Mac. Robertson Land continental slope. The most prominent channel, Wild Canyon, extends from the shelf break to the full depth of the slope, trending north before turning NW at 65° S (facing downslope). Its full length is over 200 km (Figs. 1, 8). Near the shelf break, Wild Canyon shows a bowl-shaped cross-section, up to 150 km in width and 2.5 km deep (Fig. 8A). The channel floor is populated by a dendritic network of numerous, mostly V-shaped, tributaries, interpreted as gullies. The gully network in Wild Canyon makes it difficult to trace reflectors laterally (along-slope) in the seismic reflection profiles (Fig. 8A).

Wild Canyon debouches into a submarine channel-levee complex fan that forms part of the continental rise (Fig. 8A). The number of tributaries reduces toward the lower slope and the morphology of the

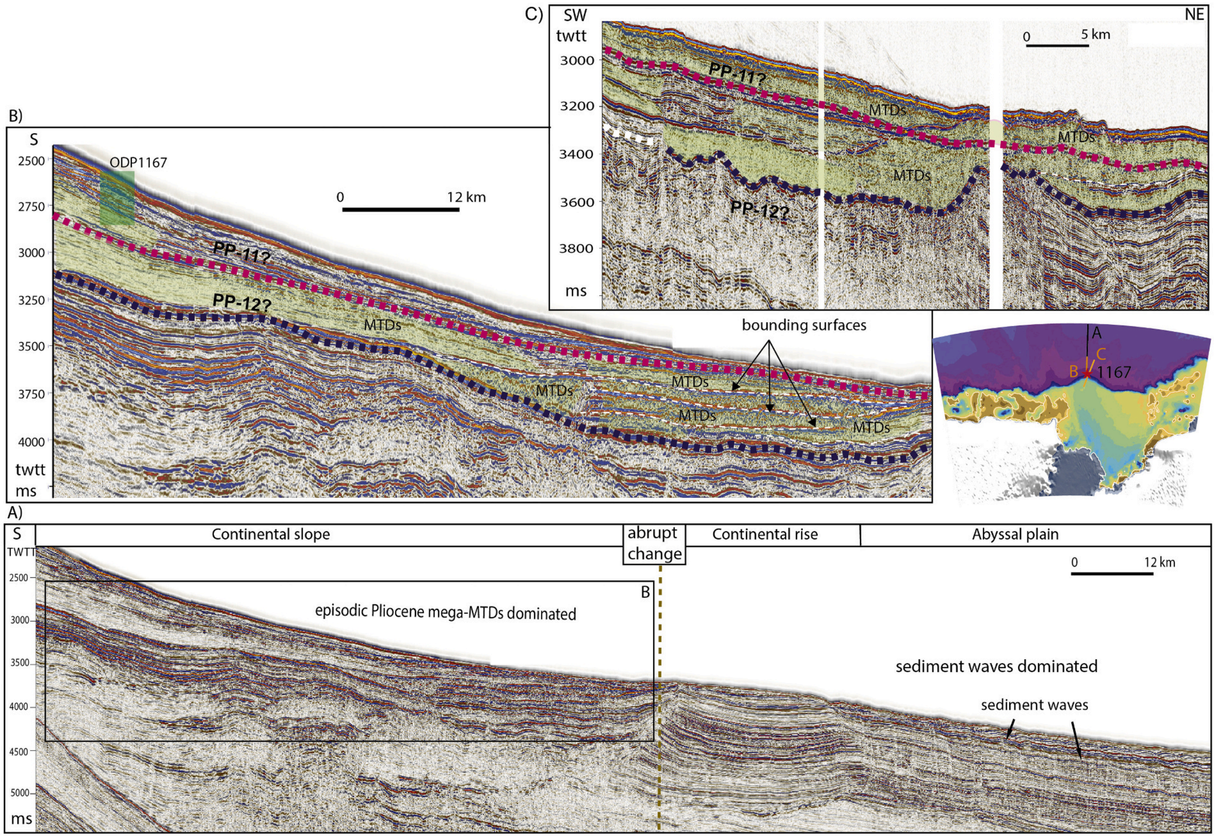


Fig. 6. Multiple episodic MTDs on the upper slope of Prydz Bay. These MTDs are also the major components of the Prydz Channel TMF. A) seismic profile across the TMF and extending to the continental rise, showing an abrupt change in sediment depositional pattern (TH99-32). The lower slope is dominated by MTDs and the rise and abyssal plain is dominated by drifts and sediment wave deposits. B) Enlarged section of the slope deposits, section shown in A. C) Another example of MTDs in a section across the TMF (line BMR33-57).

Wild Canyon shifts from bowl- to V-shaped (Fig. 8B). Here the canyon becomes shallower (from 1.9 to 1 km) and narrower (from 120 km to 100 km). The western flank of the channel exhibits an erosional surface characterized by slump deposits comprised of chaotic or semi-transparent seismic reflectors and a steep headwall (Fig. 8B). In contrast, the eastern flank displays lenticular sediment ridges composed of lateral bedded facies with subparallel, continuous stratified reflections of low to medium amplitude (Table 1, Fig. 8B). These lenticular ridges are interpreted as levee deposits. The reflectors converge and thin away from the channel axis (Fig. 8B). This pattern, of remobilization on the western flank with a levee deposit on the eastern flank, is repeated for the un-named channel located to the east of Wild Canyon (Fig. 3). Farther to the east of Wild Canyon, two prominent sediment ridges referred to Wild Drift and Wilkins Drift (Fig. 1) have been interpreted to have developed the onset of the Antarctic Circumpolar Current (ACC) at around the time of the Eocene-Oligocene boundary and details were described by Kvaas and Leitchenkov et al., 1994).

4.5. Sediment waves

On the continental rise of the Mac Robertson, some seismic lines show packages of wavy reflectors, with upstream asymmetric geometry, as observed in faceis E (Fig. 9). Facies E is interpreted here as climbing sediment waves (Allen, 1963; Rubin and Hunter, 1982) and they have been recognized in overbank areas of the Wild Canyon along the slope and on the continental rise (Fig. 9A and B). Sediment waves are long-lived, especially on the distal levee of the Wild Canyon in ~4000 m water depth located above reflector PP-12 (Fig. 9). The onset of sediment-wave formation remains unconstrained; however, these sediment waves are long-lived with an onset well below PP-12 (before the early Pliocene) and persist until today (Fig. 9). The reflector patterns of chaotic to continuous, parallel reflectors suggest coarser turbidites filled in the Wild Canyon (Fig. 9B).

The height of the sediment waves and the wavelength decreases away from the channel with wavelength decreasing from 3 to less than 1 km (Fig. 9B). The waves are interpreted as having been deposited from overbank flows, which shows upslope migration (Fig. 9A). The seismic reflections profiles reveal varying internal structures and geometries with changing amplitude in the sediment waves (Fig. 9). The internal acoustic facies shows transparent reflections with low amplitude between PP-11 and PP-12. The sediment waves have an asymmetrical cross-section (Figs. 9A, B) which results from a slower rate of sediment deposition on the downstream, steeper (lee) flank compared with a more rapid rate on the gentler (stoss) flank. The size of sediment waves in this area is increased above the key reflector of PP-11 toward the upper slope and the Wild Canyon (Fig. 9A).

5. Discussion

5.1. Wild Canyon and the role of Coriolis effect

Wild Canyon (Fig. 8) and adjacent channels that originate from tributary networks of gullies on concave areas of the upper slope of the Mac. Robertson margin display a similar morphology: overbank levees deposited adjacent to the eastern flank of Wild Canyon display evidence for aggradation, whereas the western flank is dominated by sediment remobilization features (Fig. 8B). A network of V-shaped tributaries of varying width and incised around 300 m on the upper slope merge downslope into Wild Canyon, which are assumed here to have originated in front of the ice sheet by at times when its grounding zone

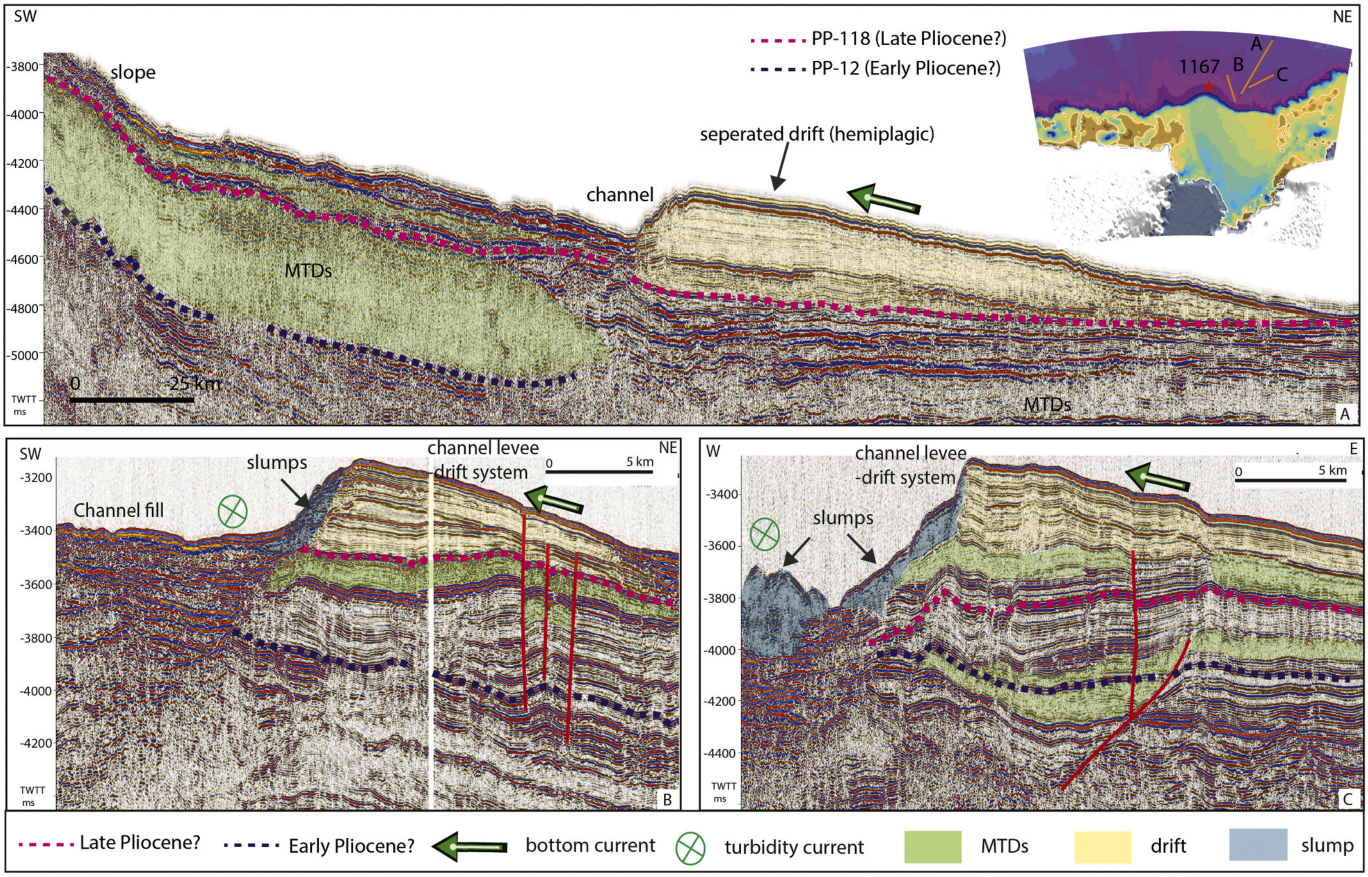


Fig. 7. Drift deposits along the east side of Prydz Channel Fan. A) seismic section (TH89-23-2) showing massive MTD deposit with sediment drift separated from the slope by a channel; B) line BMR33-21, seismic section located to the NW of section "A" showing faulting and slumping of the drift deposit. Slumping is a possibly associated with down-slope flowing turbidity currents; C) seismic section located to the SE of sections "A" and "B" showing faulting and slumping of the drift deposit (BMR33-12).

advances to the shelf break through the action of turbidity currents. The establishment of an absolute chronology for the initiation and development of Wild Canyon remains uncertain because well-dated sediment records from the study area are not available.

Asymmetry and westward migration of the canyon may potentially be attributable to the influence of the Coriolis effect. The Coriolis effect arises from Earth's rotation and so remains constant over geological time scales independent of variations in sediment transport and flow activity (Cossu and Wells, 2010). Turbidity currents are deflected to the left in the southern hemisphere leading to high deposition rates and high levees on the left channel flank and lower levees on the right-hand sides of channels when the turbidity currents are non-erosive and deposition is dominated by suspension fall-out (Cossu and Wells, 2013; Huang and Jokat, 2016).

This is the prevalent situation almost everywhere around Antarctica, as through most of the Neogene and Quaternary deposition has prevailed over erosion. Further partial remobilization of the left bank drives the migration of channels to the left. Even beneath the axis of major channels there has been net deposition, as illustrated by the aggradation of the seismic facies containing strong reflectors beneath the thalweg of Wild Canyon in Fig. 8B.

5.2. Channels versus trough mouth fan slope settings

The Prydz Bay and Mac. Robertson Land margins show contrasting sedimentary architectures. Sediment transport along the Mac. Robertson Land margin is localized in several major channel systems, particularly the Wild Canyon, and few MTDs are present (Figs. 3, 7, 8, 10). The Prydz Bay margin, in contrast, is dominated by theTMF and gravity flow deposits such as MTDs (Figs. 2, 4A, 5, 6 and 10). The architecture of prograding sequences in TMFs on the upper continental slope, and the formation of submarine channels associated with them, is a response to the geomorphology of the continental margin, slope gradient and sediment supply (O'Cofaigh et al., 2003; (Nielsen et al., 2005). The mounded signature and chaotic seismic reflections of the Prydz Channel Fan indicate its composition of numerous large submarine MTDs (Figs. 5, 6), during the Plio-Pleistocene. Glacigenic sediments transported to the shelf break during ice-sheet maxima were the primary sediment input into the Prydz Channel Fan. The internal reflection geometry of the associated TMF is difficult to map, showing mostly chaotic seismic facies because of the dominance of MTDs (Figs. 5, 6). ODP drilling Site 1167 on the TMF recovered gravity flow deposits, that is mainly composed of poorly sorted and glacially influenced sediments, predominantly diamictons (Passchier et al., 2003; Cooper et al., 2008; O'Brien et al., 2007).

The gradient of the continental slope exerts a fundamental control on the processes of margin sedimentation and, hence, on the resulting slope morphology and sediment architecture (O'Cofaigh et al., 2003). Slopes steeper than ca. 4° prevent the build-up of TMFs and instead represent a favorable setting for the formation of turbidity currents eventually leading to submarine channel development, as we observe on the steep (4–6°) Mac. Robertson continental margin (Fig. 10) with its narrow (60–80 km) shelf. Channels (e.g. Wild Canyon) and gullies characterize the upper slope and testify to reworked by turbidity currents generated by slope failures.

Besides pre-existing slope geometry and slope gradients, the amount of sediment delivered to the continental shelf break plays a more important role. Sediment was supplied to the different sectors of the

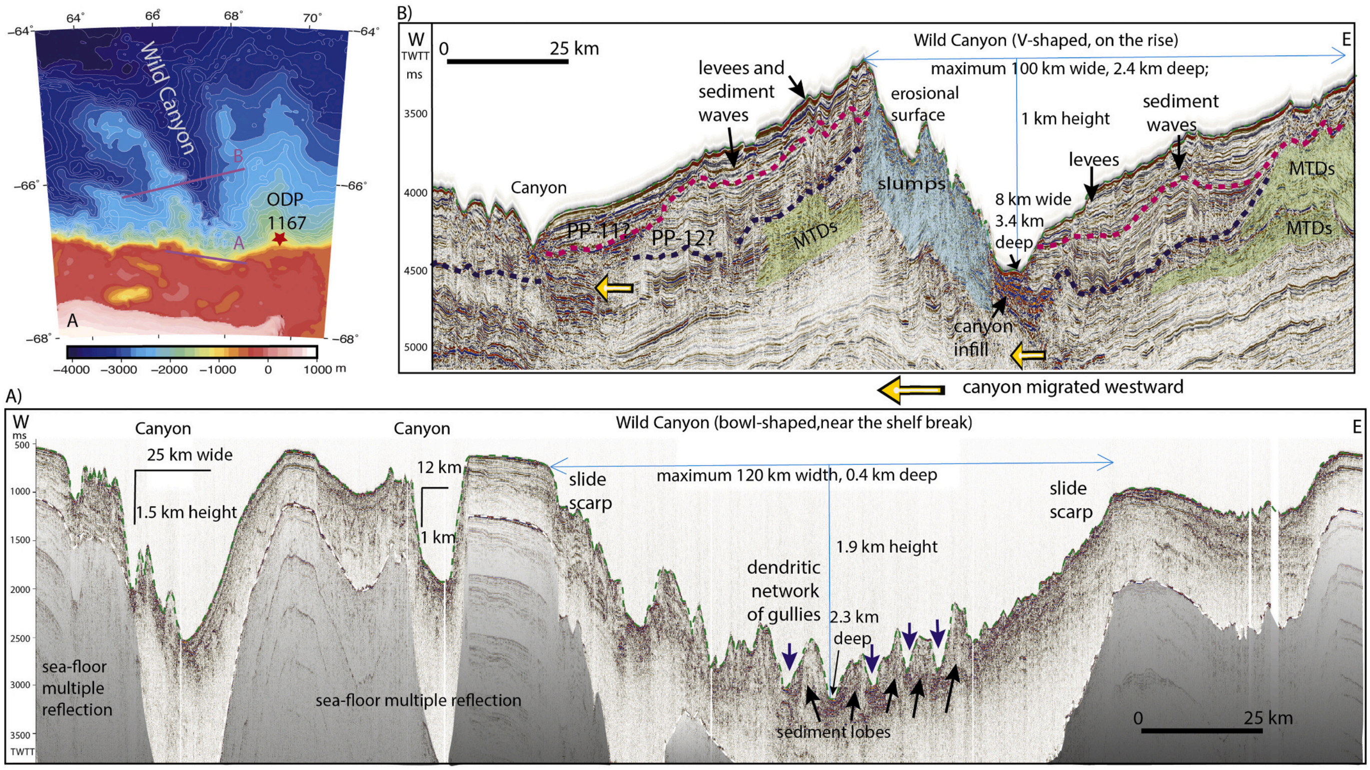


Fig. 8. The changing geomorphology of the Wild Canyon from the Mac. Robertson Land shelf break (A: line BMR33-05) to the slope (B: BMR33-11).

margin, particularly where TMFs deposition occurred. Most TMFs are located offshore large glacial troughs (O'Cofaigh et al., 2003; Dowdeswell et al., 2008) where past ice streams likely delivered large amounts of sediment that built up the actual fan. The TMF deposition has reduced the angle of the continental slope, while progradation on smaller fans and in the interfan areas has increased the gradient. There

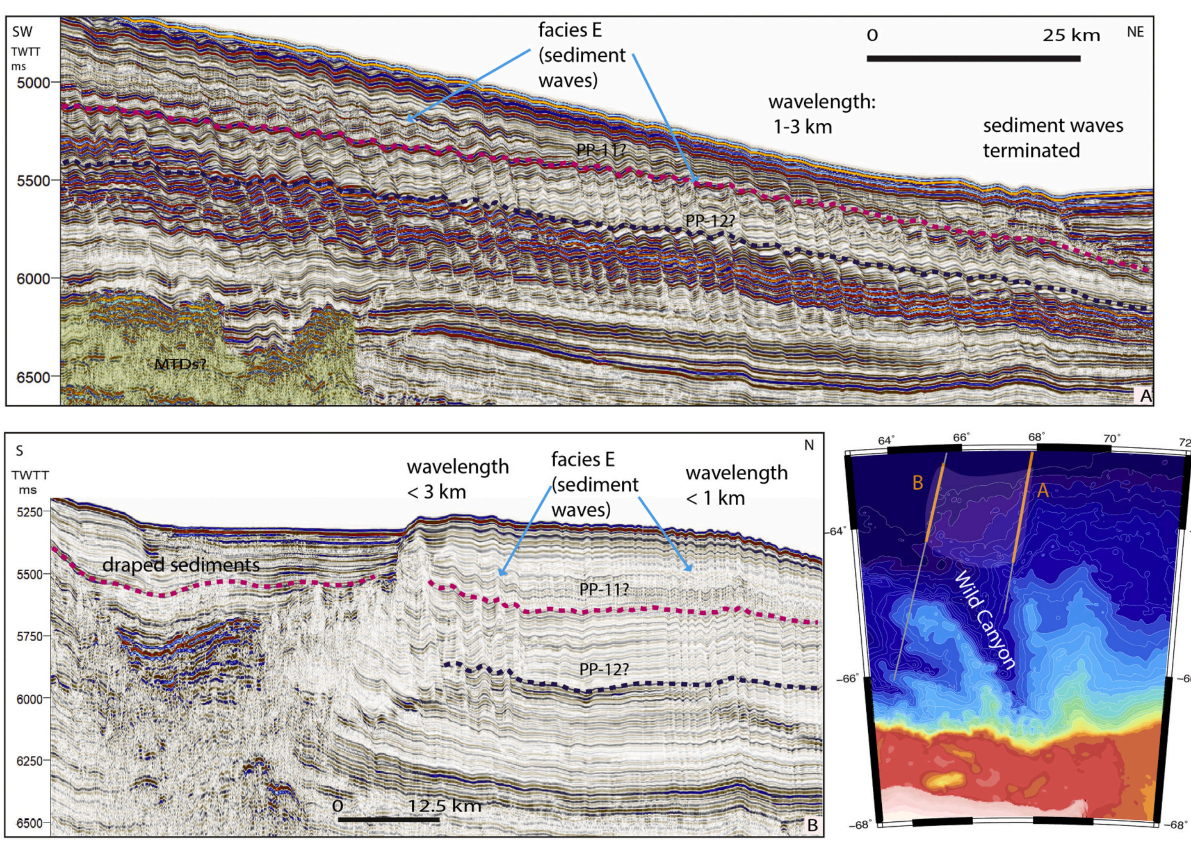


Fig. 9. Sediment waves developed on the levee flanks of the Wild Canyon from the continental slope (A: GA229-31) and rise (B: line GA228_06).

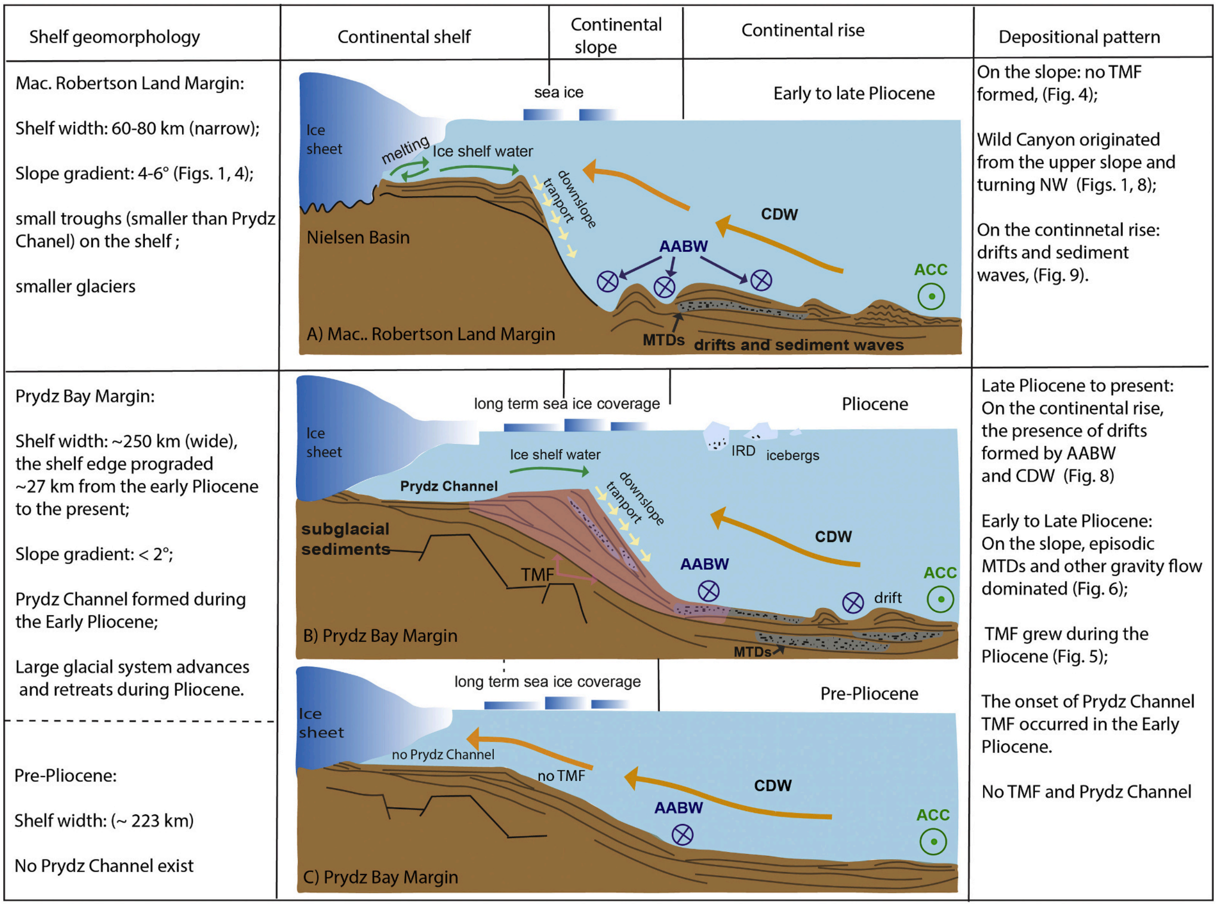


Fig. 10. Summary of the differences between the Mac. Robertson Land and Prydz Bay margin.

is evidence of net accumulation of sediment along the entire seismic line (Fig. 8A). Beneath the gully axes there are successions exhibiting high amplitude reflections that record progressive accumulation (Fig. 8A). On the lower slopes on the flanks of the bowl there is net depositions indicated by the reflectors that are approximately conformal with the seafloor. The main difference between the upper slope of the Mac. Robertson Land and the adjacent TMFs is in the balance between the fraction of sediment delivered to the shelf edge that has remained on the slope versus the fraction that has been transported further from the margin. In the case of the TMF sediments are glacial diamict stacked as clinoforms as the margin prograded seawards during glacial maxima. Deposition was focused at the mouth of a cross shelf glacial trough formed by an ice stream. Similar to the George V Land margin (De Santis et al., 2010; Post et al., 2010) there were no large ice streams delivering sediment to the shelf edge.

The formation of submarine channels such as Wild Canyon, are believed to have originated following one of two main scenarios: a) via erosive turbidity flows; or b) via retrograde slope failure (Shepard, 1981). In the former (turbidity current) scenario, the channel is initiated by repeated erosion and various downslope processes (Canals et al., 2002; Amblas et al., 2006; Noormets et al., 2009). Turbidities may be triggered by a large amount and rapid meltwater discharge near the shelf break (Michels et al., 2002; Montelli et al., 2019). Repeated turbidity flows cause the channel remobilize some of the glacigenic sediment at the shelf break and on the upper slope to incise the shelf break and transport this down slope until it finally reaches the foot of slope where it deposited to build levees submarine fans.

The second (retrograde slope failure) scenario calls for channels to be initiated by slope failures. Sediment mobilized by slumping becomes focused into gullies forming a turbidity flow that extends into a channel down-slope. Failure of the gully headwall causes them to grow up-slope until their headwalls eventually breaches the shelf break; most channel on Earth are slope-confined blind channels which must have evolved initially by this mechanism (Harris et al., 2014). It is not known which of these two scenarios (turbidity currents or retrograde slope failure) explains the origin of Wild Canyon. Multibeam mapping and sediment coring coupled with an ice sheet model are needed to reconstruct subglacial hydrology and to test this hypothesis.

The Wild Canyon and other submarine channels act as conduits for turbidity currents and debris flows from the glaciated margins of Mac. Robertson Land and Prydz Bay to the deep sea. Between the channels, sediment deposition resulted principally from either channel overspill or via unconfined turbidites on the upper- to middle slope, with distal sedimentary processes modulated by contour currents. The channel levees are commonly characterized by a reflection pattern consisting of subparallel layers that converge away from channel axes, deposited as a result of overspill from channelized turbidity currents, and observed as sediment ridges that are elongated down-slope. Sediment drifts are formed by the action of bottom currents that are considered to flow along the bathymetric contours (Kuvaas et al., 2005). However, sediment drift elongated almost perpendicular to the margin, particularly off the Antarctic Peninsula, Amundsen Sea, and our study region. We interpreted this drift type as channel levee-drift system, which was formed by both alongslope bottom current and downslope turbidity currents coexisting (Rebesco et al., 2007, Uenzelmann-Neben and Gohl, 2012, Huang et al., 2014, Huang and Jokat, 2016).

The TMF was built by the expansion of the Lambert Glacier, which has formed a large glacial trough during the Early Pliocene (Cooper and O'Brien, 2004). Other factors may also impact the growth of the TMF. The low gradient of Prydz Bay slope facilitated incremental development of a TMF by debris-flow deposition during glacial maxima. MTDs are restricted to those areas in which the gradient of the upper 1000 m of the continental slope is < 1°. However, experimental studies suggest that slope gradient is a secondary factor in determining whether or not a debris flow evolves into a turbidite. A more important factor is whether or not the composition of the sediment preconditions a debris flow to dilution (Talling et al., 2002). Regional and continent-wide early to middle Pliocene warm intervals that can cause sea-ice and continental ice sheet retreat, which may be related to rapid sea level rise, increased subglacial meltwater erosion. Warming temperatures and increased meltwater discharge should have increased the sediment flux (Cowan et al., 2020), which further contributed to the formation of the TMF and its associated MTDs.

5.3. Paleoclimatic implications

O'Brien et al. (2007) showed that glacial sediments, geomorphological features and over-compacted sediments were deposited in Prydz Bay from the earliest Oligocene at the time the East Antarctic Ice sheet first formed. Our seismic interpretation confirms that it was not until the early Pliocene (3.9–3.6 Ma) that the ice stream incised the shelf forming Prydz Channel and deposited the Prydz Channel Fan (Fig. 1). The development of the TMF led to a change in slope geometry, from a slope built over oblique, prograding clinoforms to one comprised of sigmoidal clinoform packages (Table 1 and Fig. 5). The shelf edge located at the end of Prydz Channel prograded by about 27 km between the early Pliocene and present (O'Brien et al., 2007).

The MTDs appear to originate from sediment excavated during early Pliocene glacial maxima from the Prydz Channel glacial trough that terminates at the shelf break. They are distinct on the upper slope and are well defined by boundary surfaces that are prominent farther downslope (Figs. 5, 6). The MTDs are cohesive debris flows comprised of deposits such as diamicton as cored at Site 1167 (Passchier et al., 2003). Climatic fluctuations are indicated by diatom assemblages recovered from Prydz Bay ODP sites 1166 and 1165 (Escutia et al., 2009; Passchier, 2011) and the presence of a thin bed of Pliocene diatomite in a diamictite-dominated succession at Site 742. These deposits have been interpreted as suggesting periods of major Pliocene recession of Lambert Glacier interspersed with its advances to the continental-shelf edge (Barron et al., 1991; Hambrey et al., 1991) as well as much reduced sea-ice cover compared with that of today. Within this context, it is possible to interpret the MTDs either as records of grounded ice advance to the shelf edge and/or of failure of the glacially over-steepened upper slope deposits during episodes of glacial retreat (Figs. 6, 7). The abundance of MTDs on the upper slope section in Prydz Bay may indicate that both processes took place.

Much terrestrially derived sediment was sequestered on the outer shelf and the upper slope, whereas sediment bypass to the adjacent slope and rise was reduced in the late Pliocene (above PP-11), as distinct shifts of depositional style occurred on the continental rise (Figs. 3, 5). Sediment drifts composed of fine-grained turbidites and hemipelagic sediments, as inferred from the acoustic layered and transparent reflections, dominated the continental rise (Figs. 3, 7, 10). We proposed that these drifts formed during the Late Pliocene possibly because of strengthened westerly winds and invigorated circumpolar ocean circulation, which resulted from the intensification of Antarctic cooling. Sediment drift deposits, in which bottom currents modulate the deposition of sediment delivered to the foot of slope by turbidity currents, have also been reported for locations along the continental rise of the Amundsen Sea, West Antarctic Peninsula, Weddell Sea, Wilkes Land Margin, and contain continuous sedimentary records of Antarctic ice sheet fluctuations (De Santis et al., 2003; Escutia et al., 2005; Rebesco et al., 2007; Uenzelmann-Neben and Gohl, 2012; Huang and Jokat, 2016). Unfortunately, late Pliocene glacial records are poorly preserved on the Antarctic continental margin. Subsequent Southern Ocean cooling and increased seasonal persistence of Antarctic sea ice occurred between 3.3 Ma and 2.6 Ma (McKay et al., 2012).

In the study region, the long-lived sediment waves are cyclic steps (Fig. 9) and may result from sediment falling from suspension carried by turbidity currents and further deposited by slow-moving contour currents. The suspended load is presumably provided by episodic turbidity current activity (both supercritical flow and subcritical flow, Symons et al., 2016) on the lower continental slope and rise together with background hemipelagic sedimentation. It is possible that the debris flows active on the upper slope are related to, and in some cases trigger, turbidity currents which travel down slope into the most distal parts of the basin. Sediment waves are associated with larger sediment drifts on the lower continental rise of Mac Roberson Land (Figs. 1, 10), that extend perpendicular to the continental margin (Figs. 1, 8B). Both the sediment waves and drift deposits are inferred to have formed by advection of fine material from turbidity currents, captured and re-deposited by westward-flowing bottom currents. The distinct depositional style from MTDs and TMF dominated on the slope to contourites and sediment waves dominated on the rise reflects the variations of turbidity currents and bottom currents during different time intervals. In the east Prydz Bay the distinct depositional style change from MTDs and thick tabular turbiditic dominated style between PP-12 and PP-11, to small slope channel-levee systems after PP-11(Fig. 7A). This vertical succession of the different stages has been interpreted in other latitude margins as the product of gradual reduction in the volume of mass flows and grain size, associated with progressive relative sea-level rise (Mutti and Normark, 1987). Hence, the change in depositional style may reflect here a shift to a more sediment starved environment in the sector of the margin, with fine, distal turbiditic and contouritic mixed depositional style after PP-11 (Fig. 7). This shift coupled with decrease in sediment also reflect that the study region has been changed from *polythermal condition* to cold-based glaciation.

In the early Pliocene, between PP12 and PP-11, the glacial input from the continental shelf and downslope processes clearly dominated on the Mac. Robertson Land margin, with a turbidite overbank deposit formed close to the margin (Figs. 8B, 9). In the late Pliocene, the sediment delivery from the shelf decreased, perhaps because of transition to drier more polar conditions. Sediments were redeposited by contour currents, leading to the formation of sediment drifts and sediment waves. The intensification of Antarctic cooling promoted a vigorous ocean circulation as more AAWB formation occurred by mixing of Circumpolar Deep Water with salty shelf water (Billups, 2002; Jacobs, 2004; Yabuki et al., 2006; Williams et al., 2016; Fig. 10). Once formed, AABW flows northwards down slope and then is deflected westwards by the Coriolis effect, where it flows along the continental rise. In the Mac. Robertson slope and rise, widespread sediment-wave development and sediment drift enhanced growth above PP-11 (Fig. 9) may reflect the intensified activity of AABW downslope flow along the Wild and other slope channels, during late Pliocene cooling.

The geomorphological and depositional setting shown by the Mac. Robertson and Prydz Bay margins has some similarities with the George Vth Land margin. In both cases a large TMF was constructed by expansion over the continental shelf of glaciers with a large EAIS drainage catchment basin: The Lambert Glacier in Prydz Bay and the Cook Glacier in George Vth Land. Gullies merging down-slope into large channels are present on the relatively steep continental slope to the west of such TMFs. The Jussieu Canyon in the George Vth Land and the Wild Canyon in the Mac. Robertson margin originated by highly energetic turbiditic processes. These channels act as preferential conduits for dense water downslope flow feeding of the AABW. The IODP Exp. 318, the IMAGE CADO and other projects revealed that the levees of the Jussieu Canyon preserve an incredible paleoceanographic archive of bottom water Cenozoic record (De Santis et al., 2010; Patterson et al., 2014, Jimenez-Espejo et al., 2020; Wilson et al., 2018; Smith et al., 2020). Our analysis suggest that such a similar record can be potentially obtained also from the levees of the Wild Canyon and provides the basis for a new IODP proposal. The record of the glacial expansion of the

Lambert Glacier provided by the ODP legs 119 and 188 will then be coupled with the paleoceanographic record of the AABW since the early Pliocene and possibly in older times, extending to earlier more accurately determine the timing of the important events that have influenced the evolution of this margin.

6. Conclusions

The geomorphologic setting of Mac. Robertson Land and Prydz Bay and their overall margin architecture evolved differently since the early Pliocene. The Prydz Bay margin is characterized by a broad shelf (∼250 km), cut by the large glacial trough of the Prydz Channel and has a low continental slope gradient (< 2°). These conditions allowed margin progradation and the deposition of a TMF. The TMF is composed of sediment gravity flows of a range of sizes including large MTDs, which can be related to periodic glacial advances during the early Pliocene. Fluctuations of the ice front during glacial maxima and subsequent sediment deposition patterns are key parameters in determining slope gradient and geomorphology.

The Mac. Robertson Land margin is relatively steeper (4–6°), with a narrower shelf (60–80 km) and it is cut by smaller glacial troughs (eg. Nielsen Basin). Only a few MTDs are observed here, while the relatively steep continental slope (up to 6°) favored high-energy flows. These conditions promote the widespread development of channels (e.g. Wild Canyon) and gullies at the upper slope, which testify to reworking by turbidity currents. The Wild Canyon steers toward to the NW on the continental rise, and is characterized by aggradation and tall right-hand-side levee deposits, and remobilization features such as slumps on the left-hand side. We attribute this pattern to the partial remobilization of the left bank drives the migration of channels to the left due to Coriolis force.

The changes of the deposition pattern from the slope to rise of both regions of the Mac. Robertson and Prydz Bay reflects the changes of sediment supply and Southern Ocean circulation since the early Pliocene. In the early Pliocene, the turbidity currents and mass-transport processes dominated and resulted in construction of a large TMF and turbiditic overbank deposits close to the margin. In the late Pliocene, sediment supply from the continental shelf decreased and contour currents reworked fine grained material, leading to the formation of sediment drifts and sediment waves on the rise. The growth of the Wild Canyon levees also occurred during late Pliocene, whereas the rest of the margin appears to be sediment starved, which reflect the intensified activity of downslope flow during the late Pliocene cooling. This work provides a crucial basis for a new scientific ocean drilling proposal aimed at recovering more expanded records from the Wild Canyon levees, in addition to the thin, distal and condensed record at IODP Site 1165, to better estimate the onset and changes of the AABW production during past climate cycles.

We attribute the observed changes in the depositional setting of Mac. Robertson and Prydz Bay margin to the Antarctic cooling in the late Pliocene, that likely promoted a vigorous ocean circulation as more AAWB formation and invigorated Circumpolar Deep Water, both as consequences of the late Pliocene onset of a more stable, cold Antarctic ice sheet.

7. Data Availability

Datasets related to this article can be found at Antarctic Seismic Data Library System (http://sdls.ogs.trieste.it), an open-source online data repository hosted at Istituto Nazionale di Oceanografia Sperimentale (OGS).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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