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Evidence for a Highly Dynamic West Antarctic Ice Sheet During the Pliocene

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Key Points:

- Seismic stratigraphic continental rise-to-shelf link from International Ocean Discovery Program (IODP) Expedition 379 drill sites on the Amundsen Sea rise
- Major prograding shelf growth in the Amundsen Sea Embayment by frequent grounded ice advances in the early Pliocene
- Extended period of ice sheet retreat in mid-Pliocene (4.2–3.2 Ma) from buried grounding zone wedges on shelf and core records from rise

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Major ice loss in the Amundsen Sea sector of the West Antarctic Ice Sheet (WAIS) is hypothesized to have triggered ice sheet collapses during past warm periods such as those in the Pliocene. International Ocean Discovery Program (IODP) Expedition 379 recovered continuous late Miocene to Holocene sediments from a sediment drift on the continental rise, allowing assessment of sedimentation processes in response to climate cycles and trends since the late Miocene. Via seismic correlation to the shelf, we interpret massive prograding sequences that extended the outer shelf by 80 km during the Pliocene through frequent advances of grounded ice. Buried grounding zone wedges indicate prolonged periods of ice-sheet retreat, or even collapse, during an extended mid-Pliocene warm period from ~4.2–3.2 Ma inferred from Expedition 379 records. These results indicate that the WAIS was highly dynamic during the Pliocene and major retreat events may have occurred along the Amundsen Sea margin.

Plain Language Summary

Collapses of the West Antarctic Ice Sheet (WAIS) during past warm times are suggested to begin in the Amundsen Sea sector. During a drilling expedition of the International Ocean Discovery Program (IODP), deep-sea sediments were retrieved from the Amundsen Sea. These sediment cores contain records of colder and warmer periods in the Pliocene (5.3–2.6 million years ago) which relate to the behavior of the WAIS. By analyzing seismic images that allow correlation of sediment layers from the drill sites to the continental shelf, we show that the shelf grew oceanward by 80 km due to the erosion of sediments below the WAIS and their deposition at the shelf break as the result of frequent Pliocene advances of grounded ice across the shelf. The shelf sediment layers contain grounding zone wedges predominantly formed during ice sheet retreat. The preservation of these grounding zone wedges testifies that they were not eroded by subsequent ice advances, with their burial requiring periods of prolonged WAIS retreat during warm intervals. This interpretation is consistent with our IODP drill core observations of a prominent decrease in terrigenous sedimentation between 4.2 and 3.2 million years ago, which indicates a highly dynamic WAIS during the Pliocene.

1. Introduction

Warm periods in the Pliocene (5.3–2.6 Ma) are considered as analogs to present and near-future climate conditions with atmospheric carbon dioxide concentrations of 350–450 ppm, global mean temperatures 2–3°C higher compared to pre-industrial levels, and a global mean sea level 10–30 m higher than present (e.g., Dutton et al., 2015; Gasson et al., 2016; Pagani et al., 2010; Westerhold et al., 2020). The behavior of Antarctic ice sheets during such warm phases is important, as the ice sheets modulate the intensity of global sea level changes. Ice sheet models indicate a partial to complete loss of marine-based sectors of both West and East Antarctic ice sheets during warm Plio- and Pleistocene super interglacials, when incursions of warm deep water into sub-ice shelf cavities near grounding zones caused melting of the buttressing ice shelves (de Boer et al., 2015; Golledge et al., 2017; Pollard & DeConto, 2020). The Amundsen Sea Embayment (ASE) in West Antarctica (Figure 1) is a key region for monitoring ice-sheet stability, since ice on this

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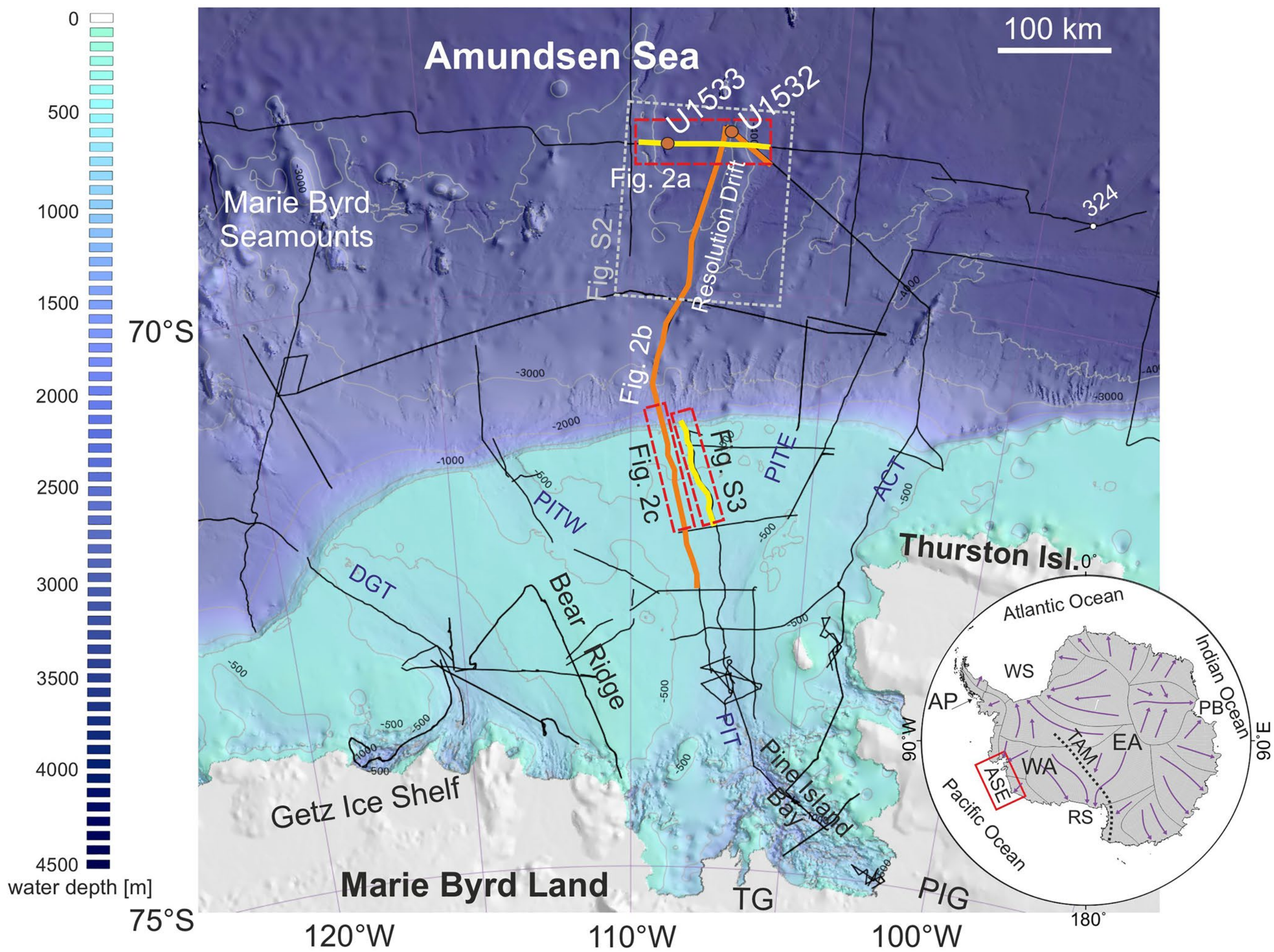

Figure 1. Amundsen Sea sector with International Ocean Discovery Program (IODP) Expedition 379 drill sites on Resolution Drift (red dots) and seismic lines (black lines). Seismic lines used in this study are in orange and yellow. Thwaites (TG) and Pine Island glaciers (PIG) formed Pine Island Trough (PIT) which divides into Pine Island Trough West (PITW) and Pine Island Trough East (PITE) on the outer shelf. Other glacial troughs are Dotson-Getz Trough (DGT) and Abbot-Cosgrove Trough (ACT). White dot marks DSDP Leg 35 Site 324. Bathymetry is from Arndt et al. (2013). Present ice divides (black lines) and flow pattern (blue arrows) are simplified from Rignot et al. (2011). Abbreviations denote West Antarctica (WA), East Antarctica (EA), Amundsen Sea Embayment (ASE), Antarctic Peninsula (AP), Weddell Sea (WS), Ross Sea (RS), Prydz Bay (PB), and Transantarctic Mountains (TAM).

margin is currently being lost at an accelerated pace, leading to rapid retreat of Pine Island, Thwaites, and neighboring glaciers (e.g., Rignot et al., 2019; Scambos et al., 2017; Smith et al., 2020). The Amundsen Sea sector is hypothesized as a precursor for major West Antarctic Ice Sheet (WAIS) retreat or even collapse during most intense warm periods of the Plio-Pleistocene over the past 5 Myr (DeConto & Pollard, 2016).

In order to address past ice-sheet dynamic processes in the Amundsen Sea sector, we analyzed seismic lines across the ASE shelf with direct connection to the two drill sites of the International Ocean Discovery Program (IODP) Expedition 379 (Gohl et al., 2021) on the continental rise (Figure 1). The ASE shelf is characterized by large cross-shelf paleo-ice stream troughs, such as Pine Island Trough (PIT) with its outer shelf western (PITW) and eastern (PITE) branches, Dotson-Getz Trough (DGT), and Abbot-Cosgrove Trough (ACT). The outer shelf shows sequences of prograding deposits, which have been identified at several locations around Antarctica and are characteristic for polar continental shelves (e.g., Anderson & Bartek, 1992; Bart & De Santis, 2012; Dowdeswell et al., 2006; Hochmuth & Gohl, 2019; Nitsche et al., 2000). Antarctic ice sheet advances across the shelves during glacial times added substantial volumes of glacially eroded sediments to the outer shelf, thereby expanding the continental shelf on average by about 7% since the onset of major glaciations (Hochmuth & Gohl, 2019). The amount of glacially induced shelf growth, however, varies strongly along the Antarctic continental margins as it relates to the location of major outlet glacier sectors and is affected by the regional tectonic architecture (Hochmuth & Gohl, 2019). Outer shelf progradation caused a ~25% shelf growth in the ASE (Gohl et al., 2013; Hochmuth & Gohl, 2019).

IODP Expedition 379 drill sites U1532 and U1533 are located on an elongated sediment drift, informally named "Resolution Drift," stretching ~300 km northward from the base of the continental slope to the abyssal plain (Figure 1 and S1). This drift and neighboring parallel drifts are flanked by deep-sea channels (Figure S2) that, predominantly during glacial periods, acted as pathways for detritus transported from the shelf down to the slope and then further across the continental rise toward the deep sea. On the continental rise, particles still in suspension were captured by eastward flowing bottom currents before they accumulated on the eastern channel flanks to form the drifts (Dowdeswell et al., 2006; Nitsche et al., 2000). Such sediment drifts are frequently observed along the Pacific margin of Antarctica (e.g., Rebesco et al., 2002; Uenzelmann-Neben & Gohl, 2012, 2014). In this type of depositional system, the highest supply of detritus occurred during glacial periods, when the grounded WAIS bulldozed large volumes of glacigenic debris to the outer shelf, from where it was redeposited down to the rise. In contrast, interglacial periods of ice-sheet retreat have a reduced time-integrated flux of downslope transported terrigenous material, which then allows enrichment of biogenic components in the drift sediments. The sediments at sites U1532 and U1533 contain unique records to study the cyclicity of WAIS advance and retreat. In particular, Site U1532 contains a sequence of Pliocene sediments with an almost complete paleomagnetic record for constraining very high resolution, suborbital scale climate variability, thus providing an opportunity to better develop climate records for the sparsely sampled pre-Pleistocene interval in the Amundsen Sea (Gohl et al., 2021).

2. Drill Site Description and Seismic Data

Prior to investigation with scientific drilling, previous models of the stratigraphic architecture and ages of shelf and rise sedimentary sequences in the Amundsen Sea (Gohl et al., 2013; Uenzelmann-Neben & Gohl, 2012, 2014) were based only on long distance or jump correlation of regional seismic reflection profiles to the seismic stratigraphy of the Ross Sea tied to Deep Sea Drilling Project (DSDP) Leg 28 sites (e.g., De Santis et al., 1999) as well as to DSDP Leg 35 and Ocean Drilling Program (ODP) Leg 178 sites west of the Antarctic Peninsula (Barker et al., 2002; Tucholke et al., 1976). Recently, shelf sediments in the ASE were drilled with the MARUM-MeBo70 sea-bed drilling device in 2017, recovering sedimentary rocks of Cretaceous to Oligocene-Miocene age (Gohl et al., 2017; Klages et al., 2020). The almost continuous sequences at IODP Expedition 379 Sites U1532 and U1533 on the continental rise (Gohl et al., 2021; Wellner et al., 2021a, 2021b) span the latest Miocene to Holocene with high core recovery rates of 90% and 70%, respectively (Figure 1). Site U1532 is located near the crest of Resolution Drift (Figure S1) and penetrated down to 794 m depth below the seafloor, exhibiting sedimentation rates of up to 61 cm kyr^{-1} within the Pliocene. Site U1533 penetrated 383 m into the lowermost western flank of this drift, in proximity to a deep-sea channel (Figures S1 and S2), and shows a more condensed sequence with sedimentation rates up to 22 cm kyr^{-1} in the early Pliocene. Preliminary investigations suggest that sediments at both sites are predominantly terrigenous, but are intercalated by pelagic or hemipelagic deposits that, in some cases, contain microfossils. Chronological control was achieved by both high-resolution magnetostratigraphy and biostratigraphy (Wellner et al., 2021a, 2021b).

Site U1532 is located at the northwestern end of seismic profile AWI-20100130, while Site U1533 is situated on profile TH86003B (Figures 2a and 2b; Figures S1 and S2). We performed correlation of horizons and unit characteristics between the seismic records of the drill sites and the continental shelf through a series of multichannel seismic profiles (Figure 1) (TH86 lines; Scheuer et al., 2006; Yamaguchi et al., 1988; AWI lines: Gohl et al., 2013; Uenzelmann-Neben & Gohl, 2012, 2014). Data acquisition and processing methods for the AWI lines are described in Gohl et al. (2013) and Uenzelmann-Neben and Gohl (2012, 2014). The single-channel seismic line NBP9902-11 on the shelf (Figure S3) displays high-quality data from the seafloor to its first multiple (Lowe & Anderson, 2002). Correlation of major reflectors from the drill sites across the continental rise to the lower slope was relatively straightforward, whereas correlation across the middle and upper slope was more challenging due to the thinning nature of seismic units with increasing slope angle and the presence of slumps and seafloor multiples (Figure S4). Careful reprocessing of line AWI-20100132, however, solved those issues, so that we were able to correlate within an uncertainty of 2–3 reflection wave-

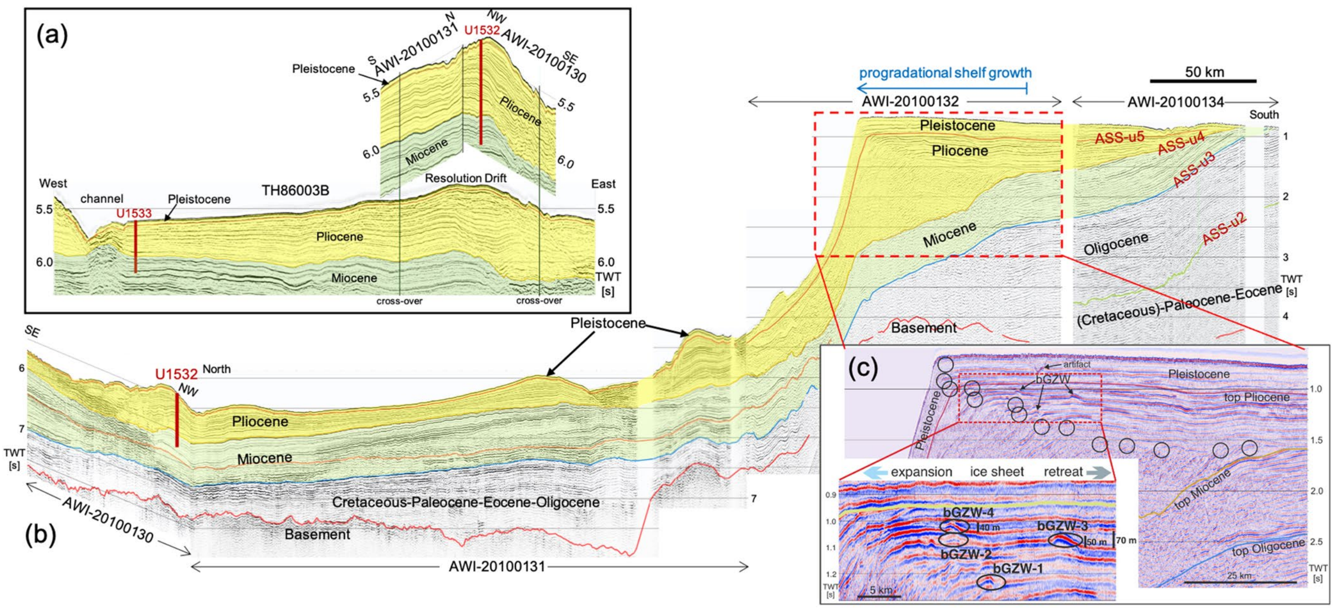

Figure 2. (a) Crossing seismic lines in area of International Ocean Discovery Program (IODP) Expedition 379 Sites U1532 and U1533 near the crest and at the lowermost flank of Resolution Drift, respectively. (b) Seismic transect from Site U1532 on the rise to the outer shelf with interpreted zones of stratigraphic ages and the basement. Shelf unconformities ASS-u2 to ASS-u5 are modified from Gohl et al. (2013). Lines AWI-20100130 and AWI-20100131 in (a) and AWI-20100130 in (b) are rotated for pseudo-3D impression. (c) Section across prograding sequences of outer continental shelf. Circles mark identified shelf breaks in the Pliocene and Pleistocene. bGZW annotates buried grounding zone wedges. Enlarged seismic image shows middle to late Pliocene zone with bGZWs. Vertical black bars mark thicknesses converted from time. TWT is two-way travel-time.

lets up or down resulting in a two-way travel-time uncertainty of ±100 ms. A further challenge was the extremely strong seafloor multiples in the seismic records from the outer shelf at water depths ≤550 m, in particular those of line AWI-20100132 (Figures 2b and 2c). Here, numerous iceberg scours carved into overcompacted seabed sediments (Graham et al., 2010; Lowe & Anderson, 2002). They generated high-amplitude diffractions, which remained present in the multiples despite the long 3000-m streamer, and thus, in conjunction with the relatively small airgun source, prevented a complete suppression of these multiples that are superposed on the lower part of the progradational reflector sequences, despite applying frequency-wavenumber (f-k) and Radon transform filtering.

3. Shelf-to-Rise Sedimentation

The seismic transect for this study is located in the eastern ASE, along the main path of grounded ice advancing from the present termini of Pine Island and Thwaites glaciers toward the outer shelf (Fig. 1; Fig. 2b). The top-of-Pliocene and top-of-Miocene seismic horizons, as identified from drill sites U1532 and U1533 on Resolution Drift (Figures 2a and S1), can be traced across the continental rise, parallel to the elongated drift, and onto the slope and shelf (Figure 2b).

In our re-evaluation of the previous seismic stratigraphic model of the ASE shelf (Gohl et al., 2013), the vast amount of sediment volume deposited within a ~80-km wide zone of prograding foresets was supplied by WAIS advances during the Pliocene (Figures 2b and 2c). Most of the sequences stratigraphically lying below the Plio-Pleistocene units and presumably being of Miocene age were aggradationally deposited, indicating that grounded ice rarely reach the shelf break, while Pleistocene contribution to progradational shelf growth was relatively small compared to that of the Pliocene (cf. Dowdeswell et al., 2006). It should be noted that magnitude of shelf growth varies in the Amundsen Sea (Gohl et al., 2013; Hochmuth & Gohl, 2013; Nitsche et al., 1997), suggesting that tectonic architecture beneath the outer shelf played a significant role for shelf growth (Hochmuth & Gohl, 2019). Seismic lines AWI-20100132 (Figure 2c) and NBP9902-11 (Figure S3) cross the outer shelf just west of the main PITE (Figure 1). Unlike the other glacial troughs (DGT, PITW, ACT), the outer PITE shows a subtle modern and paleo-bathymetric difference (<100 m) over a

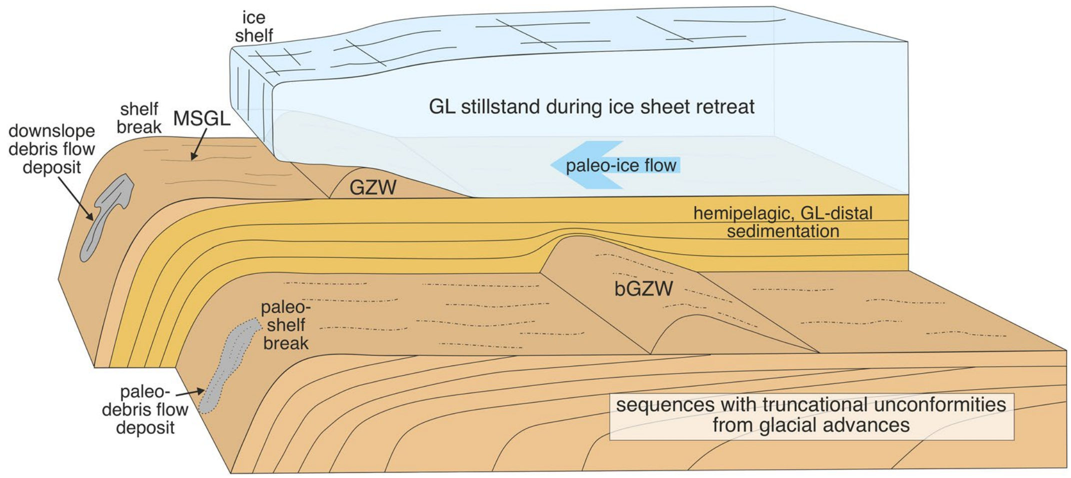

Figure 3. Conceptual model illustrating outer shelf sequences with buried grounding zone wedges (bGZW) that are preserved due to prolonged intervals of sedimentation unaffected by grounded ice advances. GL: grounding line; MSGL: mega-scale glacial lineation.

broad outer shelf area (Graham et al., 2010), which indicates that the ice stream widened on the outer shelf (Wellner et al., 2001).

The Pliocene and Pleistocene prograding wedge (Figures 2c and S3) contains distinct paleo-shelf break features from seismic interpretation, indicating a minimum of 14 glacial advances across the outer shelf throughout this period. As grounded ice repeatedly eroded some of the shelf sediments and their depositional shelf-break signature, this is a minimum estimate (cf. Bart et al., 2007), and the realistic number of outer shelf growth events is likely higher. Notably, in the seismic record of the outer shelf, a number of buried grounding zone wedges (bGZWs) is observed at or near the upward doming part of the sequences (Figure 2c). Tracing the bottom and top reflections of the bGZW zone onto the middle shelf south of the oldest onset of progradation, where the aggradational Pliocene layer reaches its full thickness, places this zone approximately into the middle to late Pliocene range. Grounding zone wedges (GZWs) are glacimorphological depositional features interpreted to result from local accumulation of sediment during a temporary halt in grounding-line retreat of an ice stream (e.g., Batchelor & Dowdeswell, 2015; Klages et al., 2015). Such GZWs are frequently observed on the modern seafloor of polar continental shelves and mark the maximum advance of grounded ice during the last glacial period or phases of grounding-line stillstands during subsequent ice retreat usually within cross-shelf troughs formed by fast-flowing ice streams (e.g., Bart & Cone, 2012; Bart et al., 2017; O'Brien et al., 1999). A number of GZWs have been identified on the middle and outer shelf along the PITE, indicating retreat stillstands since the last glacial maximum (Graham et al., 2016; Jakobsson et al., 2012). The preservation of the Pliocene bGZWs on the ASE shelf indicates that their formations were followed by periods of hemi-pelagic deposition in a presumably glacimarine environment without erosive glacial advances (Figure 3). The observed bGZW-2, -3 and -4 are 3–4 km in along-flow direction with crests 40–50 m high (based on a seismic interval velocity of 2,100 m/s derived from stacking velocities) and have the typical asymmetric wedge shape with a steep seaward flank downstream of the paleo-ice flow direction (Figure 2c). The lowermost imaged wedge (bGZW-1) shows an atypical, slightly steeper upstream flank. However, it is possible that this feature (a) is imaged obliquely by the corresponding seismic line, or (b) represents a paleo-shelf break bGZW, or (c) a lateral shear moraine (Batchelor & Dowdeswell, 2015; Dowdeswell & Fugelli, 2012).

Undisturbed sequences between the bGZWs can be used to estimate time periods without ice grounding events occurring in this area. Such an undisturbed sedimentary layer is observed between bGZW-2/-3 and bGZW-4 with a thickness of 50–70 m (Figure 2c), which is substantially thicker than the ~20-m vertical resolution limit of the seismic record. As drill core records from the outer ASE shelf do not exist to enable precise determination of age and duration of this sedimentary unit, we estimate an average sedimentation rate of 22 cm kyr^{-1} from the total Pliocene (2.75-myr timespan) layer thickness of 600 m south of the onset of shelf progradation (Figure 2c). This is a minimum rate for the entire Pliocene, because sequences eroded by grounded ice cannot be accounted for. The Pliocene sedimentation rate is higher than at other Antarctic outer shelf drill sites, for example, 8.6 cm kyr^{-1} for the early Pliocene (5.12–4.25 Ma) on the western Antarctic Peninsula (Bart & Iwai, 2012) and a minimum rate of 5.4 cm kyr^{-1} for the mid to late Pliocene in the Ross Sea (McKay et al., 2019). Our estimated sedimentation rate for the outer ASE shelf suggests that deposition of the 50–70 m thick undisturbed layer between bGZW-2/-3 and bGZW-4 took about 227–318 kyr, an interval corresponding to 5–7 obliquity cycles in Earth's orbit. Ross Sea drill records indicate that during the Miocene and early Pliocene obliquity acted as the dominant orbital forcing of glacial/interglacial changes archived in sedimentary facies (Naish et al., 2009).

For comparing our seismic observations from the ASE outer shelf with IODP Expedition 379 drill records on the rise, we consider sedimentation rates and variations in the distribution of biogenic material in the drift sediments. We take into account that drift sedimentation is significantly controlled by ocean-bottom currents and not only by direct sediment supply from the nearby shelf and surface waters. Both drill sites (Figure 1) predominantly contain thinly laminated silty clay of variable biogenic content, with the occasional presence of dispersed sands and gravel. For this study, we consider only the Site U1532 record because of its higher linear sedimentation rate and higher temporal resolution.

Most Site U1532 cores contain lithological facies dominated by terrigenous detritus, suggesting deposition mainly during phases of colder climate, when plankton productivity was suppressed due to (nearly) permanent sea-ice cover (Hepp et al., 2006). Results show that terrigenous sedimentation dominated from the late Miocene to about 5.0 Ma in the early Pliocene. From 5.0 to 4.2 Ma, some sequences comprise a low to common diatom presence, potentially associated with more favorable climate conditions. With the exception of one interval, sedimentation rates were relatively high in the early Pliocene with a maximum of 61 cm kyr^{-1} between 4.63 and 4.49 Ma. Some sediment intervals contain higher amounts of biosiliceous material, indicating a more pelagic and hemipelagic sedimentation, likely associated with phases of lower supply of glacigenic debris from the shelf. These sediments often contain pebbles indicating increased concentration of iceberg-rafted debris (IRD). The drill depth interval from 90 to 240 m spans the stratigraphic age range from 4.2 to 3.2 Ma and exhibits a relatively high abundance of diatoms (Figure 4). The interval from 4.2 to 3.2 Ma with the highest diatom abundance correlates with decreasing sedimentation rates to 18 cm kyr^{-1}, continuing to decrease throughout the late Pliocene and Pleistocene.

4. Discussion and Conclusions

Our integrated analysis of seismic stratigraphy, age constraints and general sedimentation characteristics from the Expedition 379 records links processes of major glacial progradation of the ASE shelf during the Pliocene to sediment deposition on a large drift on the continental rise about 280 km offshore from the shelf break. Bathymetric data show that the deep-sea channels starting at the slope base run seaward parallel to the elongated drift (Figure S2), suggesting that glacigenic detritus originating from the shelf provided most of the terrigenous drift sediments via gravity-driven transport running through the channels, with bottom-current capture and subsequent deposition of their suspended load on the drift. Although drift sediments can contain far-traveled components delivered by bottom currents (e.g., Hillenbrand & Ehrmann, 2002), initial shipboard analyses of the clay mineral provenance of the drift sediments showed that the assemblages at Sites U1532 and U1533 are characterized by the occurrence of the clay mineral kaolinite (Wellner et al., 2021a), indicating a predominant source on the ASE shelf (e.g., Ehrmann et al., 2011). While this rather rules out significant bottom-current delivery of far-traveled detritus, a clear separation of drift sediments into proximal components directly supplied from the nearby shelf and distal components supplied from the wider ASE shelf cannot be made at this stage.

The prograded wedge with lateral shelf growth of up to 80 km (Figures 2c, S3 and S4) formed in the early Pliocene (before ~4.2 Ma) and, to a smaller extent, in the late Pliocene (after ~3.2 Ma) and Pleistocene. We identified a minimum of eight early Pliocene, three late Pliocene and three Pleistocene ice-sheet advances associated with the seaward migration of the shelf-break (Figure 2c). The actual number of ice-sheet advances to the outer shelf is probably higher as not all may have reached the shelf edge (e.g., Klages et al., 2017), and some shelf-break formations were possibly eroded by a later grounded ice advance. Our

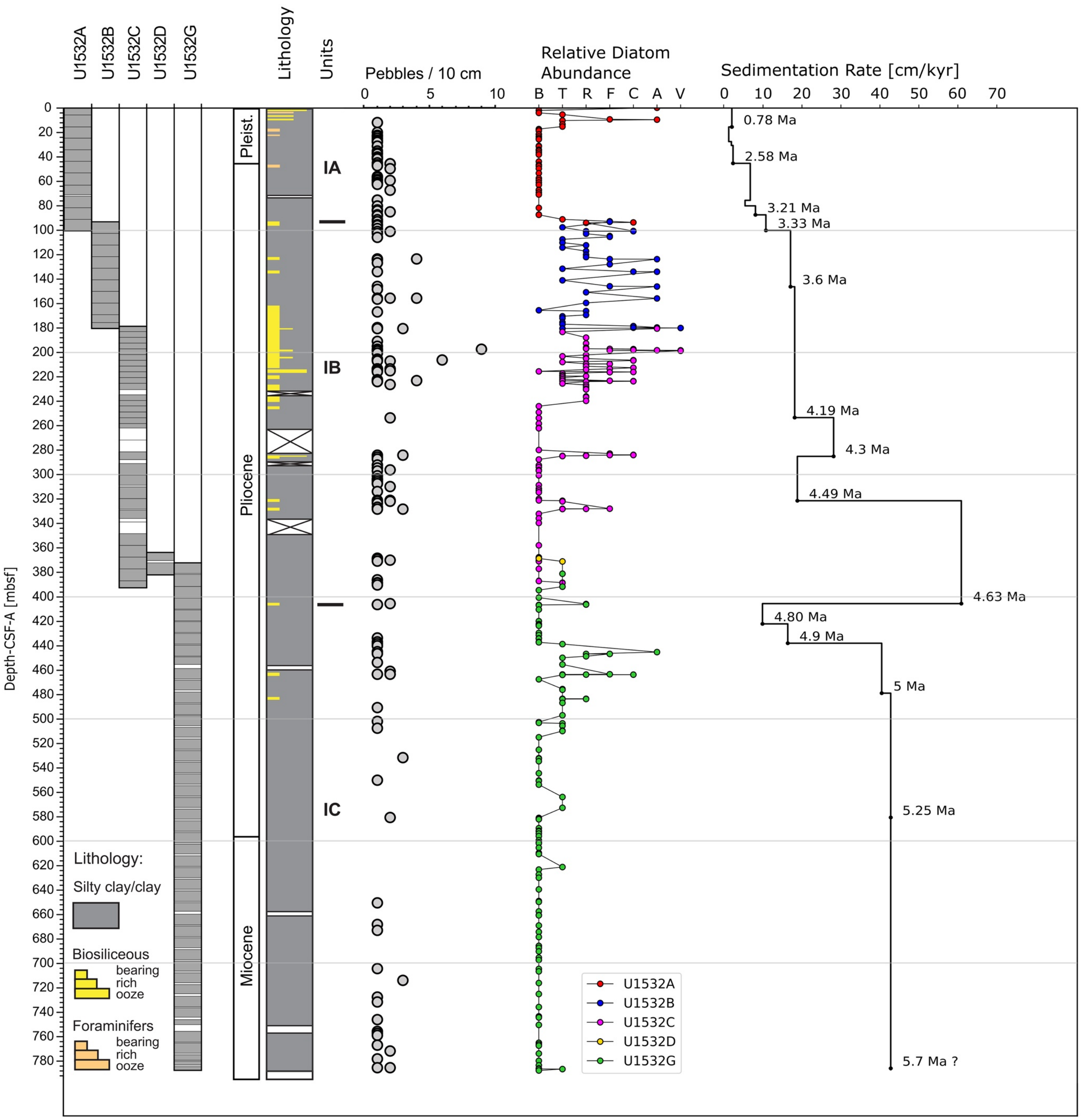

Figure 4. Lithology units, pebble abundance (visually counted number of clasts >4 mm per 10 cm core interval), relative diatom abundance, stratigraphic ages and sedimentation rates from shipboard analysis of drill cores from International Ocean Discovery Program (IODP) Expedition 379 Site U1532 (Gohl et al., 2021; Wellner et al., 2021a). Diatom abundance in smear slides is categorized as barren (B; 0%), trace (T; <2%), rare (R; 2%–5%), few (F; 5%–10%), common (C; 10%–20%), abundant (A; 20%–40%), and very abundant (V; 40%–60%). Gray shading of drill cores indicates core recovery. CSF-A is Core Depth Below Sea Floor-A.

observations are consistent with the hypothesis by Bart (2001) on major expansion of the Antarctic ice sheets in the early Pliocene. The high sedimentation rates on Resolution Drift during the early Pliocene documented by the Expedition 379 records are presumably related to major shelf progradation during this period, which resulted in high sediment supply to the rise.

Several bGZWs are observed in the Pliocene sequences of the outer shelf (Figure 2c). Such glacimorphological features are only preserved when grounded ice does not override and erode them soon after their formation. The preservation of the bGZWs together with the thick sediment layer deposited during the time interval between formation of bGZW-2/-3 and bGZW-4 suggest deposition of this layer during a prolonged period, when the WAIS was receded and did not advance beyond the middle shelf. We infer from these data that no major WAIS advance occurred over many orbital cycles (~5–7 obliquity cycles) in the mid-Pliocene. This interval may have been dominated by interglacial deposition of meltwater plumites and IRD in a possibly temperate glacimarine setting, where subglacial bedforms can be quickly buried (e.g., Dowdeswell & Vasquez, 2013; Dowdeswell et al., 1998). Alternatively, biogenic-rich material, as recorded in the early to mid-Pliocene diatomites in the AND-1B core from the Ross Sea and in ODP Leg 178 cores of Sites 1095 and 1096 from the western Antarctic Peninsula, indicating warm climatic conditions and high sedimentation rates (Escutia et al., 2009; McKay et al., 2012), may have dominated sedimentation on the ASE shelf. Both scenarios are consistent with the higher abundances of diatoms and IRD in the mid-Pliocene section of Site U1532, especially from 4.2 to 3.2 Ma (Figure 4). This interval may have been an extended period of WAIS retreat with high sedimentation rates on the shelf, causing rapid burial of subglacial bedforms. Reduced downslope transport resulted in the accumulation of hemipelagic, microfossil and IRD-enriched deposits on Resolution Drift under sedimentation rates lower than before 4.2 Ma (Figure 4). Our hypothesis of a long-term WAIS retreat is based on the observation of the bGZW zone, but the determination of the exact time span of this interval can only be tested by future drilling into these shelf sequences.

Our study results for the Amundsen Sea are consistent with the global climate record of generally elevated global temperatures for the mid to late Pliocene (Lisiecki & Raymo, 2005; Westerhold et al., 2020) (Figure S5). The extended warm period inferred from our study falls into a period of Pliocene sea-level highstands from 4.39 to 3.27 Ma (e.g., Dumitru et al., 2019), but occurred earlier than the so-called mid-Pliocene or mid-Piacenzian Warm Period (e.g., Dowsett et al., 2016; Raymo et al., 2018). Our results also compare to an extended period of open-water deposition on the Ross Sea shelf (McKay et al., 2012; Naish et al., 2009). At least when considering processes on broad scales of several orbital cycles, the Amundsen and Ross Sea sectors of the WAIS appear to have behaved in phase. The enormous shelf growth in the ASE, interrupted by long periods of glacial retreat, indicates that this drainage sector of the WAIS was highly dynamic in the Pliocene, likely acting as precursor to phases of partial or complete WAIS collapse since the establishment of a continent-wide ice sheet.

Appendix A

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Data Availability Statement

Drill core data from IODP Expedition 379 are available from http://web.iodp.tamu.edu/LORE/. Seismic data files of profile TH86003B are available from https://sdls.ogs.trieste.it, and those of profiles AWI-20100130, -0131, -0132 and -0134 are available from https://doi.pangaea.de/10.1594/PANGAEA.931266, https://doi.pangaea.de/10.1594/PANGAEA.931265, https://doi.pangaea.de/10.1594/PANGAEA.931268, and https://doi.pangaea.de/10.1594/PANGAEA.931263.

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