AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

TECHNICAL REPORTS: METHODS

10.1002/2017GC007081

MeBo70 Seabed Drilling on a Polar Continental Shelf: Operational Report and Lessons From Drilling in the Amundsen Sea Embayment of West Antarctica

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Key Points:
- First operation of a multibarrel seabed drill device in Antarctica
- Eleven holes at nine sites with max drilled depth of 35.7 m and recovery of 7%–76%
- Cores sampled Cretaceous to Holocene shelf sediments

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Citation:
Gohl, K., Freudenthal, T., Hillenbrand, C.-D., Klages, J., Larter, R., Bickert, T., . . . van de Flierdt, C. (2017). MeBo70 seabed drilling on a polar continental shelf: Operational report and lessons from drilling in the Amundsen Sea Embayment of West Antarctica. *Geochemistry, Geophysics, Geosystems*, *18*, 4235–4250. https://doi.org/10.1002/2017GC007081

Received 22 JUN 2017
Accepted 1 OCT 2017
Accepted article online 16 OCT 2017
Published online 17 NOV 2017

Abstract A multibarrel seabed drill rig was used for the first time to drill unconsolidated sediments and consolidated sedimentary rocks from an Antarctic shelf with core recoveries between 7% and 76%. We deployed the MARUM-MeBo70 drill device at nine drill sites in the Amundsen Sea Embayment. Three sites were located on the inner shelf of Pine Island Bay from which soft sediments, presumably deposited at high sedimentation rates in isolated small basins, were recovered from drill depths of up to 36 m below seafloor. Six sites were located on the middle shelf of the eastern and western embayment. Drilling at five of these sites recovered consolidated sediments and sedimentary rocks from dipping strata spanning ages from Cretaceous to Miocene. This report describes the initial coring results, the challenges posed by drifting icebergs and sea ice, and technical issues related to deployment of the MeBo70. We also present recommendations for similar future drilling campaigns on polar continental shelves.

1. Introduction

The significant role that the polar regions play in current changes in the global climate state is undisputed. A wide range of observations over recent decades has shown rapid changes in some ice sheet sectors and sea-ice extents in both hemispheres, and the effects these changes have on global climate and sea level are the subject of intensive ongoing research. While observations of the current environmental state and changes have advanced enormously, climate records of the geological past still remain poorly sampled, although onshore and offshore sedimentary deposits contain valuable records of past climate, sea-ice, and ice sheet dynamics of time periods that, for instance, represent analogues to present rapid changes. The remoteness of the polar regions, combined with their harsh weather, ice conditions, and narrow seasonal time window for expeditions, is the main reason for the lack of drilling operations, despite the urgent need for drill samples of rocks and sediments for geological and paleoclimate research communities.

A single deep-drilling research campaign, Integrated Ocean Drilling Program (IODP) Expedition 302, took place in the central Arctic Ocean in 2004 (Backman et al., 2006). The Antarctic continental margin, in contrast, has a better coverage of deep penetration drill sites with Deep Sea Drilling Project (DSDP) Legs 28 (Hayes & Frakes, 1975) and 35 (Hollister & Craddock, 1976), Ocean Drilling Program (ODP) Legs 113 (Barker et al., 1988), 119 (Barron et al., 1989), 178 (Barker et al., 1999), and 188 (O'Brien et al., 2001), International Ocean Discovery Program (IODP) Expedition 318 (Escutia et al., 2011), as well as CIROS-1 (Barrett, 1989), Cape Roberts Project (CRP) (Cape Roberts Science Team, 1999, 2000), and ANDRILL (e.g., Naish et al., 2009) drilling campaigns. However, most of these drill sites are located in more frequently visited and, thus, surveyed areas such as the Ross Sea, Antarctic Peninsula, and Prydz Bay, and only a few lie in less intensely studied areas at the Wilkes Land margin and off western Dronning Maud Land. The main reason for the lack of drilling operations in the Arctic and Antarctic, despite the urgent need for drill samples of rocks and sediments for geological and paleoclimate research communities, is the remoteness of the polar regions,

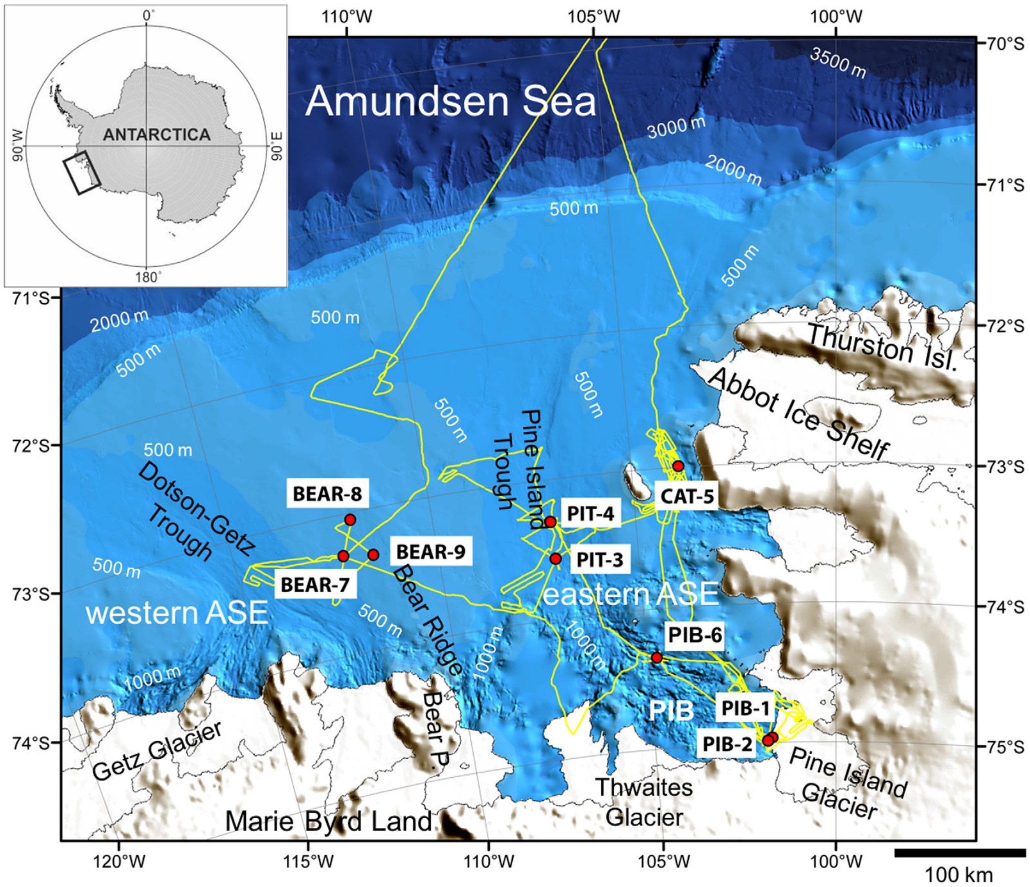

Figure 1. Bathymetric map of the Amundsen Sea Embayment (ASE), West Antarctica, with labeled MeBo70 drill sites (red dots) of expedition PS104. Yellow lines mark the ship track. Bathymetry is from the International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0 (Arndt et al., 2013). PIB = Pine Island Bay.

combined with their harsh weather, ice coverage for most time of the year and narrow seasonal time window for expeditions. These circumstances make not only drilling campaigns but also the necessary site data collection logistically challenging and costly.

Small-sized drill rigs that can be installed and operated on research icebreakers and ice-strengthened research vessels are a viable option to overcome this shortcoming and access shallow drilling targets in ice-proximal realms of the continental shelves that cannot be penetrated with conventional sediment coring techniques such as piston, gravity, and vibrocoring. Kristoffersen et al. (2000) were the first to use a light mining drill rig deployed from a research vessel, drilling 15 m into glacigenic sediments in 212 m water depth on the Dronning Maud Land shelf, East Antarctica. The SHALDRIL-I and II projects deployed a purpose-designed temporary ship-mounted drill rig from the icebreaker *Nathaniel B. Palmer* on glacially formed shelves of the northern Antarctic Peninsula (Anderson et al., 2007, 2011; Anderson & Wellner, 2011; Wellner et al., 2005). By mounting a rig over a moon pool on the starboard side of the vessel, drill pipe could be lowered to the seafloor, allowing successful coring of late Eocene to Holocene sediments by the SHALDRIL teams (Anderson & Wellner, 2011).

We used—for the first time—a multibarrel seabed drill rig to recover unconsolidated sediments and consolidated sedimentary rocks from an Antarctic shelf. The objectives of this expedition included the recovery of sediment samples for reconstructing conditions of the West Antarctic preglacial environment and its transition into the glacially dominated domain, as well as sampling Quaternary high-resolution records of the marine-based West Antarctic Ice Sheet (WAIS) which may have collapsed several times during the Neogene and Quaternary (e.g., Barnes & Hillenbrand, 2010; Naish et al., 2009; Scherer et al., 1998), and which is currently undergoing a dramatic, ocean-driven retreat in the Amundsen Sea sector (e.g., Pritchard et al., 2012;

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Table 1
Detailed Information on the MeBo70 Deployment and Recovery of Sediments

Drill site	Polarstern station no.	Coordinates (lat, lon)	Water depth (m)	Drill target (s)	Thickness of postglacial drape on midshelf (m)	Drilled depth/deployed core length (m)	Recovered core (m)	Recovery	Recovered lithology	Remarks
PIB-1 (inner Pine Island Bay)	PS104/006-2	74°57.961′ S 101°45.067′ W	1,051	Quaternary/Holocene	n/a	23.95/23.75	7.78	33%	Very soft, fine to coarse grained glacimarine and pro/subglacial sediments (mud, muddy sand and sand in uppermost part of core, and muddy to sandy diamicton below)	Test site; drilling stopped due to iceberg approach
PIB-2 (inner Pine Island Bay)	PS104/009-2	74°59.201′ S 101°52.325′ W	989	Quaternary/Holocene	n/a	16.90/16.70	3.91	23%	Very soft, fine to coarse grained glacimarine and pro/subglacial sediments (mud, sandy mud, muddy sand)	Drilling stopped due to iceberg approach, core 8 lost in drill hole; second attempt failed due to flush-water pump failure
PIT-3 (central Pine Island Trough)	PS104/020-2	73°34.095′ S 107°05.626′ W	946	Oldest dipping strata (near outcropping basement) (Cretaceous/Paleogene?)	~10	30.80/23.55	5.89	25%	Grey sandy mud, muddy sand, and sand in uppermost part of core, Qtz-rich sandstone below; carbonaceous mudstone in lowermost part of core, contains abundant microfossils, fossil plant particles, and pollen	Uppermost 10 m flushed through; slow drilling progress of the last 3 m; drilling abandoned due to iceberg approach; complete loss of diamonds on surface set drill bit (abrasion by quartz grains)
PIT-4a (central Pine Island Trough)	PS104/021-2	73°18.290′ S 107°06.635′ W	882	Dipping strata above seismic unconformity ASS-u2 (Oligocene to Miocene?)	~3	5.10/4.95	3.09	62%	Brown mud, sandy mud, and diamicton in upper cores; grey-olive stratified mudstone in lower cores; very stiff dark grey diamicton and mudstone in core catchers; low diversity of nanofossils in mudstone sample	Difficulties in retrieval of uppermost core, then drilling continued; jammed inner barrel caused temporary halt of drilling; failure to grab barrel (human error) and iceberg approach caused end of drilling

Table 1. *(continued)*

Drill site	Polarstern station no.	Coordinates (lat, lon)	Water depth (m)	Drill target (s)	Thickness of postglacial drape on midshelf (m)	Drilled depth/deployed core length (m)	Recovered core (m)	Recovery	Recovered lithology	Remarks
PIT-4b (central Pine Island Trough)	PS104/021-3	73°18.327′ S 107°06.550′ W	882	(same as PIT-4a)	~3	9.80/9.65	7.36	76%	Brown mud in core 1; grey-olive stratified mudstone with thin layers of authigenic carbonate in cores 2–5; large granitic clast on top of upper section in core 3; rare, low diversity of nanofossils of Miocene (?) age in mudstone	Drilling stopped because drill head released barrel due to malfunction of releaser; granite clast possibly pushed down from core 2 into core 3
CAT-5 (Cosgrove-Abbot Trough)	PS104/024-2	72°59.713′ S 103°50.347′ W	520	Stacked grounding-zone wedge (GZW); top of uppermost wedge	~8	2.75/2.60	0.18	7%	Olive-brown clast-supported diamicton	Drilling stopped after unwanted unscrewing (glued thread) of bottom-hole assembly part and failure to screw it back on. Damage to the umbilical (cable slipped from A-frame cable block) while MeBo was back on deck led to a time-consuming repair. After the umbilical repair, very strong and strengthening winds forced abandonment of site
PIB-6 (south-central Pine Island Bay; deep basin in southern Pine Island Trough)	PS104/038-1	74°20.982′ S 104°44.450′ W	1,453	Deep basin in Pine Island Bay (paleo-subglacial lake deposits?)	n/a	35.65/32.25	15.65	49%	Brown, olive and grey mud, sandy mud, muddy sand in upper part of core, and sand and muddy diamicton in lower part of core	Uppermost 10 m flushed through; drilling stopped because of sediment ingress into drill string causing problems with retrieving lowermost inner core barrel (successfully retrieved); jammed drill string thread during trip out

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Table 1. *(continued)*

Drill site	Polarstern station no.	Coordinates (lat, lon)	Water depth (m)	Drill target (s)	Thickness of postglacial drape on midshelf (m)	Drilled depth/ deployed core length (m)	Recovered core (m)	Recovery	Recovered lithology	Remarks
BEAR-7a (western Bear Ridge flank)	PS104/040-2	73°17.826′ S 112°19.400′ W	483	Older part of dipping strata on western flank of Bear Ridge	∼2	5.35/5.20	0.94	18%	Brown mud, sandy mud and gravelly sandy mud on top, dark olive grey diatom-rich sandy mudstone, and mudstone below	Drilling stopped due to jammed inner core barrel causing overshot shear pin breakage (cores and barrels successfully retrieved).
BEAR-7b (western Bear Ridge flank)	PS104/040-3	73°17.832′ S 112°19.395′ W	483	Older part of dipping strata on western flank of Bear Ridge (same as BEAR-7a)	∼2	17.97/17.72	8.82	50%	Olive mudstone and sandy to gravelly mudstone in upper part of core, very dark grey gravelly sandy mudstone in lower part of core (transition in core R4); some cores with isolated pebbles on top (washed through?)	Drilling stopped because of loss of flush water
BEAR-8 (western Bear Ridge flank)	PS104/041-1	73°03.188′ S 111°58.025′ W	415	Younger part of dipping strata on western flank of Bear Ridge	∼2	7.45/7.30	0.89	12%	Olive muddy sand and gravelly sandy mudstone in upper part of core, dark grey diamictite below	Drilling stopped due to jamming inner core barrel causing overshot shear pin breakage (cores and barrels successfully retrieved)
BEAR-9 (western Bear Ridge flank)	PS104/042-1	73°19.875′ S 111°34.827′ W	356	Older part of dipping strata on western flank of Bear Ridge	∼2	6.15/6.00	2.40	40%	Brown soft sandy diamicton on top, dark olive diamicton, and sandy diamicton in lower part of core, pebbles at base (pebbles probably downhole contamination)	Drilling stopped because three drill bits worn out during drilling and very slow drilling progress

Note. The thickness of the postglacial drape at the drill sites on top of the older, northward dipping strata of the middle shelf is estimated only from the Parasound records. The low core recovery and content of the upper parts of the drill holes do not allow a clear identification of the boundary to the strata below the drape.

Scambos et al., 2017; Turner et al., 2017). We deployed the MARUM-MeBo70 seabed drill device (Freudenthal & Wefer, 2013) from the icebreaking RV *Polarstern* during Expedition PS104 (February–March 2017) to the Amundsen Sea Embayment of West Antarctica. The concept of this approach was to collect deep-penetration (up to 70 m) samples of unconsolidated sediments as well as to drill through the last glacial till layer and overlying postglacial drape to collect samples from consolidated older shelf sediments, where they crop out close to the seafloor. Eleven boreholes at nine sites were drilled into isolated basins of Pine Island Bay on the inner eastern shelf and into the dipping strata of older shelf sequences of previously undetermined composition and ages (Figure 1 and Table 1).

This report presents our experience in operating the MeBo70 seabed drill device in Antarctic ice, weather, and in different lithologies. Preliminary results for a few samples obtained on board are also summarized. While detailed analyses of the drill records will be published in subsequent research papers, this report provides valuable information for the international community on drilling strategies including choices of drill tools with respect to selected drill sites and targets. We present recommendations for future campaigns using seabed drill rigs in challenging Antarctic and Arctic regions.

2. Drill Operations

2.1. Seabed Drill Device

The seafloor drill rig MARUM-MeBo70 (Figure 2) is a robotic drill that is deployed on the seabed and remotely controlled from the vessel (Freudenthal & Wefer, 2013). The complete MeBo70 system, which includes drill, winch, launch, and recovery system, control unit as well as workshop and spare drill tools, is shipped in seven 20 ft. containers. A steel-armored umbilical cable with a diameter of 32 mm is used to lower the 10 tonnes device to the seabed, where four legs are extended in order to increase the stability of the rig. Copper wires and fiber-optic cables within the umbilical are used for energy supply from the vessel and for communication between the MeBo70 and the containerized control unit on deck of the vessel. The maximum deployment water depth in the current configuration is 2,000 m.

The mast with the remotely controlled barrel and tool feeding system forms the central part of the drill rig. The drill head provides the required torque and rotary speed for rock drilling and is mounted on a guide carriage that moves up and down the mast with a maximum push force of 4 tonnes. A water pump provides seawater for flushing the drill string, for cooling of the drill bit and for removing the drill cuttings.

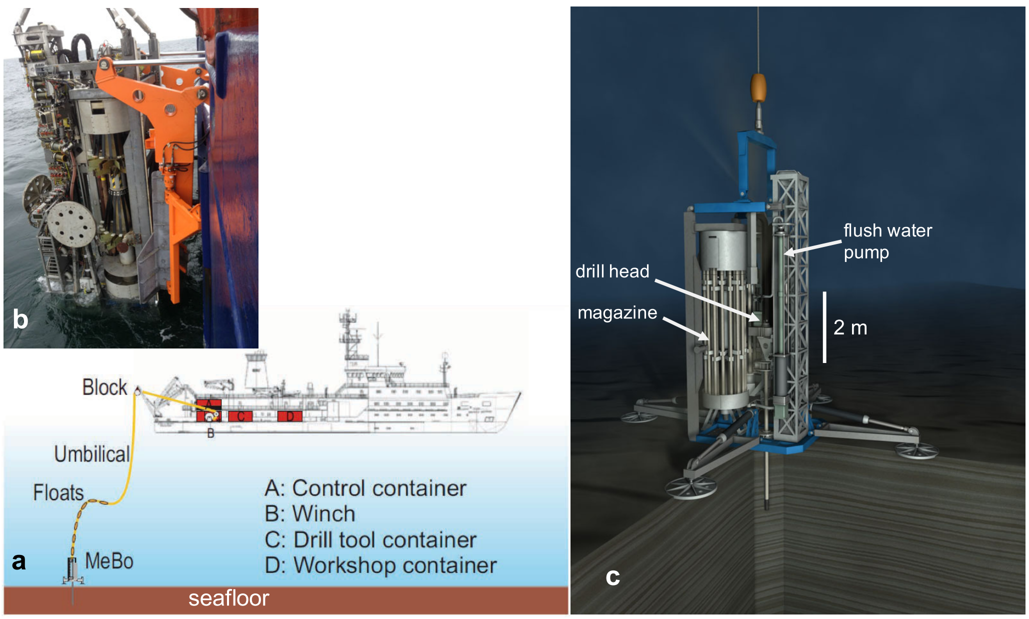

Figure 2. (a) Schematic overview of the MARUM-MeBo70 seabed drill rig and its deployment from a research vessel, (b) photo of MeBo70 before deployment from the stern of RV *Polarstern*, and (c) an artist's image of its position on the seafloor.

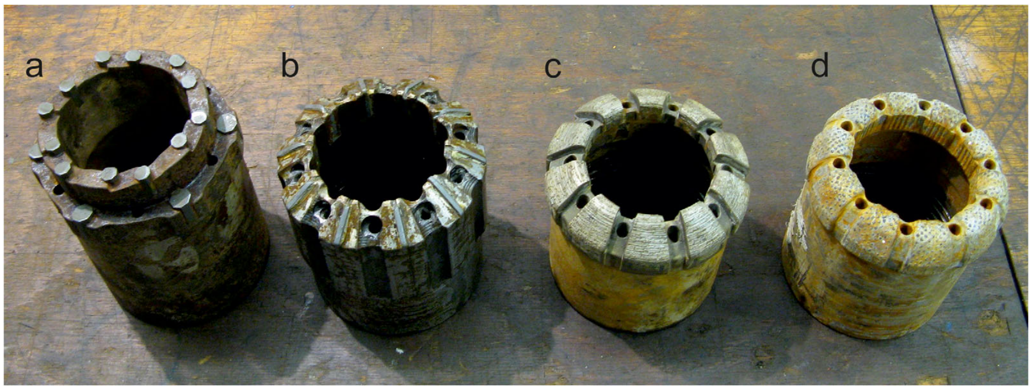

Figure 3. MeBo70 drill bits used during PS104: (a) two step tungsten carbide bit, (b) conical tungsten carbide bit, (c) diamond-impregnated bit, and (d) surface-set diamond bit.

Core barrels and rods are stored on two magazines on the drill rig. We used wireline core barrels with hardened steel and diamond drill bits (Figure 3). The bits were used in combination with pilot core lifter cases for soft sediments (push coring, 55 mm core diameter) and hard rock core lifter cases (rotary drilling, 63 mm core diameter). The stroke length was 2.35 m. With the magazines completely loaded, a maximum coring depth of more than 70 m can be reached in principle. Station time of the vessel normally exceeds 24 h per deployment. This long station time of the vessel is an important risk issue in polar waters due to drifting icebergs and massive ice floes as the umbilical connection to the MeBo drill rig allows only a relatively small maneuvering radius of up to 50 m.

A spectral gamma ray (SGR) probe was used for borehole logging (Figure 4). The probe is equipped with a 25 cm long scintillation crystal combined with a photomultiplier. Light impulses that are generated by gamma ray collisions with the scintillation crystal are counted and their energy spectra are analyzed. The three naturally occurring gamma ray emitters—potassium (K), uranium (U), and thorium (Th)—generate different energy spectra. A *GeoBase* software package is used to calculate a best fit of the spectra. By combining the results of the spectrum fit with the gamma ray counts, the concentrations of K, U, and Th are calculated. The SGR probe was used as an autonomous tool. When reaching the maximum coring depth, the inner core barrel is replaced by the probe. The sensor's center of gravity is located about 60 cm above the drill bit and measures through the drill pipe. The probe is hooked up the borehole together with the drill pipe during recovery of the drill string (logging-while-tripping) or can be deployed by open-hole wireline. Tripping speed was about 0.6 m/min.

A newly developed autonomous acoustic borehole logging tool (Figure 4) was tested during PS104. This sonic probe is equipped with a transmitter and two receivers located 90 cm and 100 cm below the transmitter, respectively. The tool is deployed in a similar way to the SGR probe during trip-out of the drill string. The sensor part is located about 1 m below the drill bit while logging the *P* wave velocity of the formation.

A temperature probe (Figure 4) was used for measuring formation temperature at different sediment depths. The probe consists of a tool that replaces an inner core barrel for conducting temperature measurements at discrete depths. The lower end of the probe is located below the drill bit at the base of the drill string and is equipped with a miniaturized temperature logger (MTL) with a 95 mm long tip. The temperature range of the MTL is $-5°$ to 50°C with a resolution of about 1 mK. The absolute accuracy is about $\pm$0.1 K. The probe is pushed together with the drill string 15 cm into the sediment. After 10 min measuring time, the temperature probe is hooked out of the drill string using the wireline technique and core drilling can proceed.

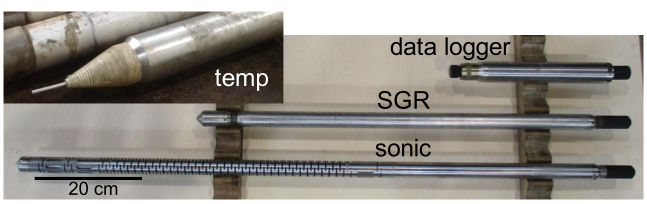

Figure 4. Downhole logging devices used with MeBo70: spectral gamma-ray (SGR) probe, acoustic (sonic) probe, and temperature (temp) probe. The data logger is mounted on top of the probe.

2.2. Site Selection

During an intensive precruise planning process, we examined data and studies on the Amundsen Sea shelf sediments based on existing multichannel and single-channel seismic reflection profiles (Graham et al., 2009; Gohl et al., 2013; Hochmuth & Gohl, 2013; Lowe &

Anderson, 2002; Muto et al., 2016; Nitsche et al., 2013), swath-bathymetric and subbottom profiler data (e.g., Graham et al., 2009, 2010; Jakobsson et al., 2011; Klages et al., 2015; Larter et al., 2009; Nitsche et al., 2007), and conventional sediment cores (e.g., Hillenbrand et al., 2013; Kirshner et al., 2012; Smith et al., 2011, 2014). The aim was to select potential drill sites for three major objectives: (1) Obtain samples from small sedimentary basins that are nested on the outcropping crystalline basement of the inner shelf. Inner shelf sites may contain high-resolution records of the Quaternary WAIS dynamics and its forcing (Hillenbrand et al., 2013, 2017; Smith et al., 2017), with some inner shelf basins containing deposits of former subglacial lakes (Kuhn et al., 2017). (2) Drill through postglacial deposits and a thin cover of last glacial till to collect drill cores from older strata that dip oceanward and are truncated close to the seafloor on the middle shelf. (3) Collect samples from grounding-zone wedges to reconstruct and understand the stabilization and retreat processes of grounded ice.

We preselected a total of 23 potential drill sites, many more than could be drilled during the PS104 expedition with 25 planned working days on the shelf. However, this selection allowed for enough contingency sites in case severe ice conditions and/or certain lithologies could not be drilled and recovered. Preexisting seismic records and, in particular, high-quality subbottom profiler (Parasound and TOPAS) data revealed sites with only 5–10 m of glacial and postglacial drape so that penetrating this drape to drill into the dipping older strata was more likely (Figure 5). With such data, an offset drilling strategy was developed in which a series of drill sites was chosen along the dipping strata to collect cores with a range of ages. Seismic and subbottom profiler records were also used to determine optimum drill sites for unconsolidated sediments in the inner shelf basins and on a grounding-zone wedge.

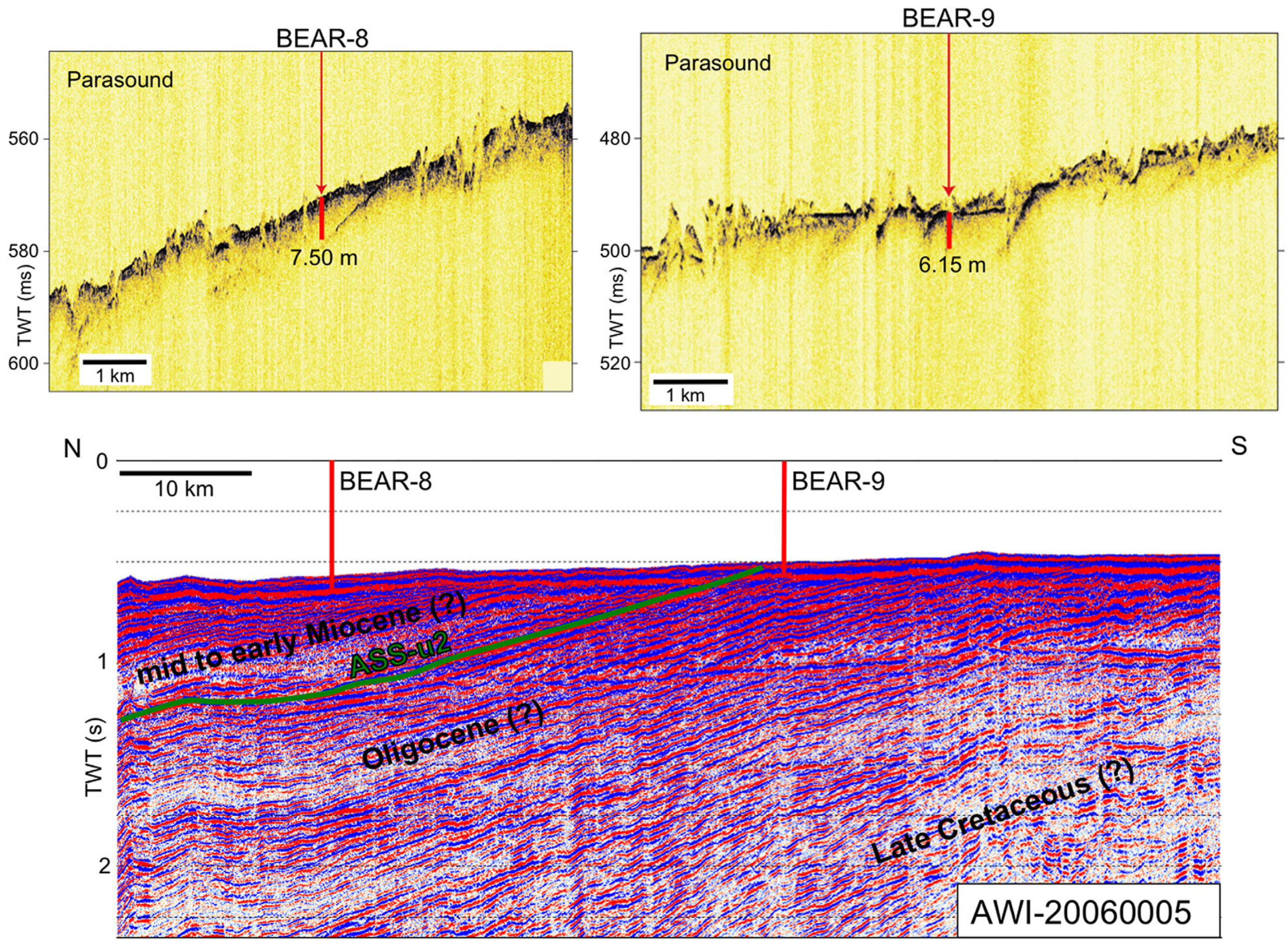

Figure 5. Seismic record from the middle shelf of the western ASE shows dipping older shelf sequence with a presumed stratigraphic age and unconformity ASS-u2 from Gohl et al. (2013). The Parasound records on top show some of the dipping layer boundaries of the sequence overlain by a thin glacial and postglacial drape at drill sites BEAR-8 and BEAR-9. The vertical axes in both record types are two-way traveltime (TWT).

2.3. Drill Sites

The MeBo70 was deployed 11 times at nine sites to recover long cores from the Amundsen Sea Embayment shelf (Figure 1). The cumulative drill rig deployment time was 193 h with 162 m drilled. In total, 150 m of sediment were cored with 56.91 m of core recovered, giving an average recovery rate of 38%. Eight temperature measurements at two stations were conducted. The SGR and sonic borehole logging probes were used at one station each. A summary of the MeBo70 deployments and core recoveries is given in Table 1.

We drilled seven boreholes at six sites (PIB-1, −2; PIT-3, −4, −6; CAT-5) on the eastern Amundsen Sea Embayment shelf. An additional four boreholes at three sites (BEAR-7, −8, −9) were drilled on the western flank of Bear Ridge in the western Amundsen Sea Embayment and targeted exclusively dipping sedimentary strata. In the following site descriptions, we list the drill sites with the applied drill strategy, tools, outcome, and technical issues. Deployment time is the total time the drill device was in the water. RV *Polarstern* station numbers are shown in parentheses after the MeBo70 site names for reference:

Site PIB-1 (PS104/006-2): At this test site, MeBo70 was deployed for 21.5 h in an isolated deep (1050 m water depth) sedimentary basin in the inner Pine Island Bay (PIB), close to the Pine Island Glacier front. Drilled depth was 23.95 m below seafloor (mbsf), cored length (10 push cores) 23.75 m, and recovery was 7.78 m of brown and olive muds, sands and grey-olive diamictons. A two-step tungsten carbide bit (Figure 3) was used in combination with pilot core lifter cases (push coring technique). Drilling had to be abandoned due to iceberg approach. We used the SGR probe for borehole logging during trip out (20.8–0.0 m depth).

Site PIB-2 (PS104/009-2): At this site in the same basin as for PIB-1, MeBo70 drilled to 16.90 mbsf and cored a length of 16.70 m (7 push cores) within 11.25 h using again the two-step tungsten carbide bit in combination with pilot core lifter cases. The drill rig recovered 3.91 m of the same type of sediments as recovered from site PIB-1. Drilling had to be interrupted, because of an iceberg passing close to the ship. A second attempt to drill at the same site had to be abandoned after 4 h without further drilling due to a failure of the flush water pump.

Site PIT-3 (PS104/020-2): This site targeted dipping older sedimentary strata cropping out near the seafloor north of the acoustic basement-sedimentary basin boundary in the southern Pine Island Trough (PIT). The strategy was to flush through about 10 m-thick (from Parasound records) overlying unconsolidated glacimarine sediments and postglacial drape with the first core barrels, followed by continuous core drilling with a surface-set diamond bit, as soon as consolidated hard strata were reached at 9.85 m below the seafloor. The drill rig was deployed for 28.25 h and drilled to 30.80 mbsf, thereby coring 23.55 m of rotary cores after flushing through most of the overburden. Drilling had to be abandoned due to iceberg approach. Ten rotary cores were retrieved, containing a total of 5.89 m of grey muddy quartz sandstone (Figure 6) and underlying carbonaceous mudstone. The drill bit was completely worn at the end of drilling.

Site PIT-4a (PS104/021-2): This site targeted dipping sedimentary strata located north of site PIT-3. We started with a two-step tungsten carbide bit in combination with rotary drilling core lifter cases. A jammed inner barrel caused a temporary halt. For the following barrels, a new bottom-hole assembly (BHA) with a diamond-impregnated bit was used. A failure to grab a barrel combined with approach of an iceberg caused the end of drilling. The deployment time was about 10 h during which a drilled depth of 5.10 mbsf with a cored length of 4.95 m was achieved. The three recovered rotary cores contained brown mud in the upper core and grey-olive stratified mudstone in the two lower cores, while very stiff dark diamicton and mudstone were collected in the core catchers.

Site PIT-4b (PS104/021-3): The second drilling attempt at the same site lasted for 16.75 h. We drilled with a diamond-impregnated bit. A new BHA with a diamond-impregnated bit was deployed after the second core barrel (4.6 m drilled depth). Total drilled depth was 9.80 mbsf with cored length of 9.65 m. Drilling stopped because the drill head released the barrel due to a malfunction of the release mechanism. Five rotary cores recovered 7.36 m of sedimentary rocks of similar lithology as retrieved from the first hole (Figure 6).

Site CAT-5 (PS104/024-2): The deployment time at this site on top of a grounding-zone wedge (GZW) in the Cosgrove-Abbot Trough (CAT) was only 3.75 h. Drilling had to be canceled due to failure of a glued thread connection within the BHA. Thus, the drilled depth was only 2.75 mbsf with a cored length of 2.60 m. The single recovered rotary core barrel that was used in combination with a diamond-impregnated bit retrieved

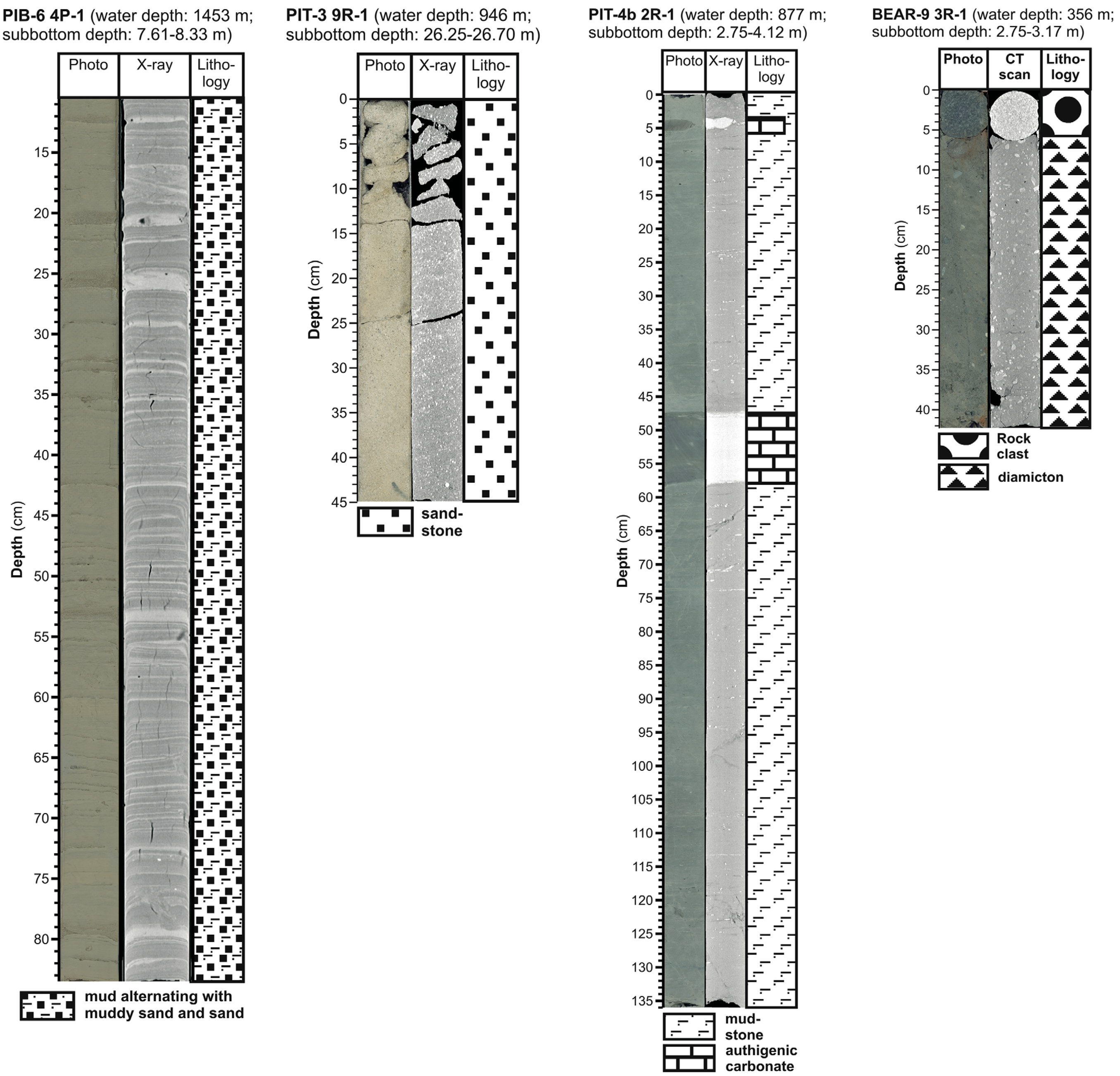

Figure 6. Examples of photo, X-radiograph, and lithology records of some of the drill cores. For lithological key, see Figure 7.

0.18 m of olive-brown sandy gravelly mud. A second attempt to drill at this site had to be canceled due to strong winds that threatened the capability of the vessel to hold station within the tight limits required for drilling operations.

Site PIB-6 (PS104/038-1): At this site, another isolated deep basin on the inner shelf along the Pine Island Trough was targeted. A maximum drilled depth of 35.65 mbsf was reached within 34.25 h using a two-step tungsten carbide bit. The cored length was 32.25 m using 14 push cores and two rotary cores. Drilling was stopped because of sediment ingress into the drill string causing problems with retrieving the lowermost inner core barrel, although this was eventually retrieved. We recovered a total of 15.65 m of brown, olive and grey muds, sandy muds, sands, and diamictons (Figure 6). Temperature measurements were conducted

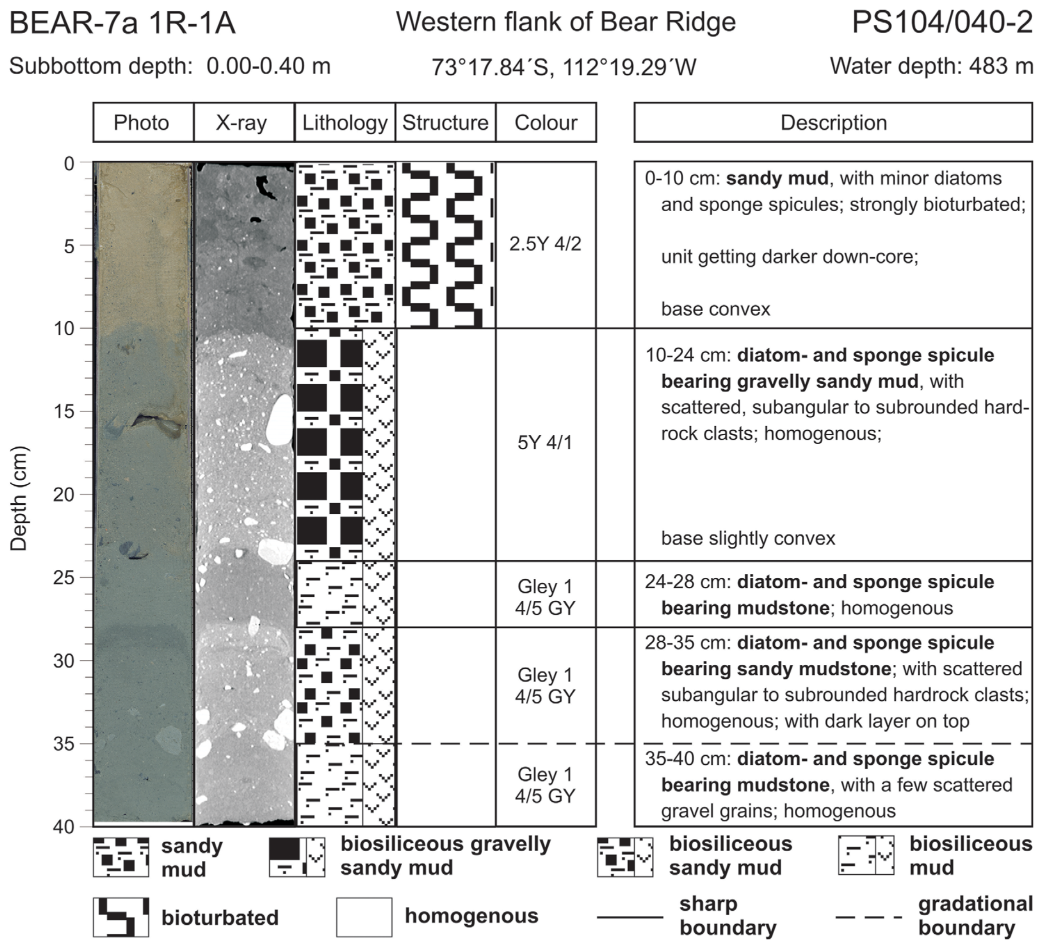

Figure 7. Photo, X-radiograph, and lithology log for the uppermost drill core from site BEAR-7A.

at 5.25, 9.95, 14.65, 19.35, 24.05, and 28.75 m. Unfortunately the five deeper measurements were affected by a slight bending of the probe that occurred during storage in the magazine after the first measurement.

Site BEAR-7a (PS104/040-2): The drill rig was deployed on top of the older part of the dipping strata at the western flank of Bear Ridge (BEAR) of the western middle shelf. Within 7.25 h, a maximum drilled depth was reached at 5.35 mbsf, and 5.20 m were cored by rotary drilling, which retrieved 0.94 m of brown mud overlying dark olive grey diatom-rich mudstone (Figure 7). The first barrel was drilled with a diamond-impregnated bit down to 2.75 m. Due to a jammed inner core barrel, the shear pin at the overshot had to be activated and only one stroke with a second BHA, again with a diamond-impregnated bit, down to 5.35 m was possible. The open-hole deployment of the SGR and sonic bore hole logging probes, fixed by the rotating chuck in the upper 2 m, were not successful due to failure of probe activation.

Site BEAR-7b (PS104/040-3): Redeployment at the same site lasted for 27.25 h and reached a depth of 17.97 mbsf. The drilled length was 17.72 m. Drilling stopped because of loss of flush water. This time a conical tungsten carbide bit was used in combination with rotary core lifter cases. The eight rotary cores collected 8.82 m of olive mudstone, which is underlain by very dark grey gravelly sandy mudstone. The bit was completely worn at the end of drilling. Despite the consolidated nature of the sediments, temperature measurements were attempted at 14.5 and 16.9 m depth. The sonic borehole logging probe and the SGR tool (SGR on wire inside the drill string, sonic during trip out below the drill bit) were used for borehole logging (16.5–0.3 m). However, the activation of the SGR probe failed.

Site BEAR-8 (PS104/041-1): The MeBo70 deployment at this site drilled down to a depth of 7.45 mbsf over 10.5 h and cored 7.30 m (3 rotary cores) with a recovery of 0.89 m. The upper cores from the younger part of the dipping sedimentary strata outcropping at site BEAR-8 (Figure 5) consist of olive diamicton, while the lower cores sampled dark grey diamicton. The first barrel was drilled with a diamond-impregnated bit down to 2.75 m. Due to indication of a jammed inner core barrel, a second BHA with a diamond-impregnated bit was used for the second core barrel down to 5.1 m. The shear pin at the overshot had to be activated due to a jammed inner core barrel, and only one stroke with a third BHA with a diamond-impregnated bit down to 7.45 m was possible. Open-hole deployment of logging probes fixed by the rotating chuck in the upper 2.1 m (SGR) and 2.8 m (acoustic) were successfully conducted.

Site BEAR-9 (PS104/042-1): At the last site of the expedition, the drill penetrated the seafloor down to a depth of 6.15 mbsf with a cored length of 6.00 m within 18.75 h deployment time. The target was to drill into the oldest part of the dipping sedimentary strata on the western flank of Bear Ridge (Figure 5). The six rotary cores and one push core collected 2.40 m of brown soft diamicton near the top (Figure 6) and dark olive mudstone in the lower part of the retrieved sedimentary column. The first three barrels were drilled down to 4 m with a conical tungsten carbide bit. Subsequently, a second BHA with conical tungsten carbide bit was deployed and drilled down to 6 m until no further progress was reached with this bit. A third BHA with a tungsten carbide bit did not achieve further progress.

3. Analysis Potential of Drilled Samples

We decided not to split the drill cores on board because of planned whole-core computed tomographic (CT) imaging after the expedition, taking into account the relatively small core diameter and the resulting small core volume. The CT scanning of the whole cores was also prioritized over splitting the cores on board, because the resulting images help to choose the most appropriate core splitting device for the sections (soft sediment core splitter and rock saw, respectively). We restricted our onboard analysis to whole-core physical property measurements using a *Geotek* multi-sensor core logger (MSCL) and preliminary assessment of smear slides taken from samples of the core tops and core catchers. The MSCL included sensors for magnetic susceptibility, *P* wave velocity, core diameter, electrical resistivity, and gamma-ray attenuation. Preliminary biostratigraphic investigations conducted onboard indicated that the recovered sedimentary strata were deposited during various times ranging from the Cretaceous-early Paleocene to the late Quaternary. These preliminary results imply that the drilled cores may have the potential to address a good part of the primary scientific objectives set out for this drilling expedition.

The presence of pollen, spores, and plant fragments in samples from the cores of the oldest (Cretaceous-early Paleocene) drilled strata (site PIT-3) and of marine microfossils in the younger (Eocene-Miocene) strata of the middle shelf (sites PIT-4, BEAR-7, -8, -9) provides constraints for the chronostratigraphy of the shelf sequences in both the eastern and western Amundsen Sea Embayment to be tied into the regional seismic reflection line network (Figure 5). If detailed palynological analysis confirms a Cretaceous-early Paleocene age for the deposits for site PIT-3, this site would contain one of the few records of the oldest sedimentary rocks sampled from the shelf bordering the West Antarctic Ice Sheet. Mesozoic sedimentary rocks have previously been sampled only from outcropping Late Cretaceous strata of the northern Antarctic Peninsula (e.g., Francis & Poole, 2002; Zinsmeister, 1982) and from the Jurassic to Early Cretaceous forearc Fossil Bluff and LeMay Groups of Alexander Island (e.g., Moncrieff & Kelly, 1993). A record from the Amundsen Sea Embayment shelf has implications for understanding of the environmental and climate conditions of West Antarctica and their greenhouse to icehouse transition from Cretaceous to Neogene times. The material indicates that there was land above sea level in central West Antarctica at this time, and that it hosted abundant and diverse vegetation, the types of which will likely constrain paleoclimate and paleoenvironmental conditions. The material may also show how taxa varied and migrated between South America and New Zealand (Bowman et al., 2016). The preliminary Oligocene to Miocene age estimates of diamictons in the BEAR site cores from the western embayment suggest that these cores may record the first advances of the ice sheet to the coast or even onto the shelf.

The few smear slide samples taken on board from the cores of the isolated inner shelf basins (sites PIB-1, -2, -6) have not revealed any microfossils so far. The terrigenous muds and sands probably originate from glaci-marine processes and gravitational debris or mud flows. The same probably applies to the recovered diamictons, which additionally may also have been deposited at the base of grounded ice. Low abundance of ice-rafted debris in large parts of the cores indicates high sedimentation rates. Although based on radiocarbon dates on the acid-insoluble fraction of organic matter only, sedimentation rates at conventional coring sites from inner shelf basins in Pine Island Bay have shown to be at least 10–20 cm/kyr (Smith et al., 2014), which is consistent with the observation of thick stratified infill assumed to be of Holocene age in acoustic subbottom profiles across these basins. Provided that ages can be assigned to these terrigenous sediments drilled with MeBo70, they may be used for reconstructing the dynamics of the Pine Island Glacier grounding line and its ice shelf (cf., Smith et al., 2017), and they may also document the existence of subglacial lakes under the expanded WAIS during the last glacial cycle (cf., Kuhn et al., 2017).

Further detailed analysis on the full core material may also yield material that can be used for both dating and proxy studies, e.g., on Late Quaternary incursions of relatively warm Circumpolar Deep Water (CDW) along the incised glacial troughs toward the grounding zone of Pine Island Glacier. CDW incursions onto the shelf have been identified as the primary cause for the present subice-shelf melting and dynamic thinning of the outlet glaciers of the Amundsen Sea Embayment (e.g., Jenkins et al., 2016; Pritchard et al., 2012; Turner et al., 2017). Recently, studies analyzing benthic foraminifera assemblages (Minzoni et al., 2017) and the chemical composition (i.e., stable carbon isotopes and magnesium/calcium ratios) of benthic and planktic foraminifer shells in marine sediments (Hillenbrand et al., 2017) showed that variable inflow of CDW was the primary driver for grounding-line retreat along the coast of the Amundsen Sea Embayment throughout the Holocene and since the 1940s.

4. Lessons Learned

4.1. Lithologies and Choice of Drill Tools

Glacial deposits are among the most difficult lithologies for core drilling. Boulders of variable size with a wide variety of lithologies with different geotechnical characteristics are imbedded in a softer, mostly cohesive matrix both in marine sediments with abundant ice rafted debris as well as in glacial tills. The selected drill bit and core lifter case have to be suitable for drilling crystalline hard rock. However, hard rock drilling usually results in low core recovery rates for soft sediments since the flush water erodes the sediment before it enters into the inner core barrel. In order to optimize core recovery rates for both soft sediments and hard rocks during rotary drilling, we used core lifter cases with lips that tend to reduce the erosional force of the flush water. With this configuration, we encountered jamming of core barrels that resulted in drilling being aborted several times. For the last two deployments (sites BEAR-9 and BEAR-7b), we changed to core lifter cases and a corresponding drill bit without lips, with the result that no further core jamming occurred. The core recovery, however, did not change significantly. Since it is not only drilling depth that can be increased by avoiding core jamming, but also the deployment of bore hole logging tools depends on the ability to recover the deployed inner core barrels, we recommend that avoiding core jamming must have higher priority than optimizing core recovery rates, if the primary objective is to investigate deeper strata by drilling in this challenging environment.

The optimal choice of drill bit was especially challenging when it was not possible from previous drilling to infer the expected lithologies. At two hard rock drilling sites, we had two deployments of MeBo70 each. At both sites, better core recovery and greater drilling depths were reached during the second deployment. Taking the time for a short pilot drilling in order to investigate the lithology enables the most suitable drill bit(s) to be selected for the deeper second drilling. While tungsten carbide and diamond impregnated bits work well in mudstone and claystone, both types experienced strong wear in the presence of sand and gravel (sites PIT-3 and BEAR-9). Diamond-impregnated bits showed lower penetration rates but were successful in all rock types encountered. Loading of several BHAs with different drill bits is recommended for being able to react to changing lithologies.

For pure soft sediment drilling (sites PIB-1, PIB-2, PIB-6), we selected a tungsten carbide bit and pilot core lifter case. This core lifter case penetrates through the drill bit. This is a very effective way to prevent flush water from eroding the sediment. However, this method only works if no larger boulders or hard rock layers are encountered. This method works very well in lower latitude cohesive continental slope sediments where core recovery rates of more than 90% were reached (e.g., Mohtadi et al., 2012). We were less successful with average recovery rates between 23% and 49% per site in Pine Island Bay and Pine Island Trough, which can possibly be explained by the presence of ice rafted debris in these sediments. The observation that recovery rate increased at site PIB-1 in depths of more than 14.5 mbsf suggest that higher compaction and increased sediment stiffness are favorable for the coring process. At site PIB-6 we experimented with weaker core catchers and achieved the best recovery rates (max 97% per core barrel). Planning additional time for pilot drilling to test the most suitable strength of the core catchers helps to optimize core recovery in these glacimarine sediments. In general, multiple deployments at most sites are essential for successful coring.

4.2. Ice

Any drilling campaign on an Antarctic margin has to deal with the risk of drifting icebergs and sea ice, which may limit the station time of the vessel during drilling. Required station time usually is between 20 and 30 h but can be up to 50 h. The deployment of a seabed drill rig requires the vessel to remain stationary with only a small maneuvering radius, which depends on the water depth, and was 20–50 m for the vessel's stern during our MeBo70 operations on the 500–1,400 m deep shelf sites. While an icebreaker such as *Polarstern* can handle loosely broken, single-year ice floes and growlers while on stationary position, encountering massive multiyear ice floes and icebergs would cause termination of the drilling operation at a particular site, as happened at four boreholes during PS104. In instances in which small-size icebergs approach the vessel, a dynamic positioning (DP) system (RV *Polarstern* is not equipped with such a system) would improve the maneuverability of the vessel to draw aside from the iceberg's drift path so that drilling can be continued at this site. Reliable ice observation techniques are essential. These include the assessment of daily satellite optical and radar ice imagery before approaching a drill site, and ice radar monitoring and tracking of massive ice fields and icebergs from the vessel's bridge during the rig deployment and drill operation. The "near real-time" processing service of the German Aerospace Center (DLR) provided us daily with very useful high-resolution radar images from the TerraSAR-X and TanDEM-X satellites. In addition, helicopter ice surveillance flights from RV *Polarstern* helped to assess the current ice situation in between satellite image intervals.

4.3. Weather

Strong katabatic winds became a problem at one drill site (CAT-5) and precluded deployment of the MeBo70 at another planned drill site. Beaufort wind force eight or more poses the risk that, if the vessel cannot stay with its bow into the wind, the stern movement radius permitted for MeBo70 operation is too small for maneuvering. This problem may be eased on vessels equipped with strong thrusters at both the bow and the stern, preferably in combination with a DP system. The effect of very cold air temperature on the MeBo70 device while on deck could not be tested, because the temperature never fell below $-4^{\circ}C$ during PS104. The greatest vulnerability to be identified was the flush water pump, which contains a reservoir of seawater. However, we were prepared with a tent-like cover and hot-air heaters, which we did not have to use. We filled the pump with glycol after each deployment.

4.4. Drill Strategy and Expectations

Seabed drilling operations in polar conditions must be considered as an opportunistic campaign. Selecting large numbers of preselected alternate drill sites is a prerequisite for deciding on contingency sites if ice, icebergs, weather, or lithological conditions require change of plans. The effort must be focused on sites—and times of the year—with the least risk of massive sea ice or iceberg encounters, because a longer operation time window allows deeper penetration and possible multiple holes at a single site. Even icebergs that are relatively small on the Antarctic scale and are near the resolution limit of commonly used satellite imagery (e.g., MODIS or even some lower resolution products from Sentinel-1) have the capacity to cause termination of drilling.

Core recovery does not seem to correlate to the degree of consolidation of the drilled material. We had high and low recoveries in both consolidated and unconsolidated sediments. Although, the seabed drilling technology turned out to be a viable tool for drilling into young, soft material, it provides best results in older, consolidated sedimentary rocks if the postglacial drape can be penetrated. However, as outlined above, there is scope for improvement in recovering soft sediments by finding the optimum combination of drill bits and core catchers. Given the irregular thickness of this drape and the unpredictable penetration depth at any site, a plan to collect continuous older strata with an offset drill site strategy across dipping sequences is difficult to achieve. However, even spot coring in such sequences will provide a wealth of useful stratigraphic and paleoclimate information.

5. Conclusions

RV *Polarstern* Expedition PS104, the first seabed drilling expedition on an Antarctic shelf, proved to be a successful campaign despite some difficulties and challenges. Drilling into dipping older, consolidated stratigraphic sequences yielded Late Cretaceous to Miocene samples for studies on preglacial to greenhouse-icehouse transitional environmental and paleoclimate processes. Unconsolidated Quaternary sediments from the inner shelf were drilled with remarkable penetration and higher than expected recovery rates despite the presence of dispersed ice-rafted debris. Our experience is that investing more time on each site for testing various drill bits and core catchers as well as push coring versus rotary coring by drilling multiple holes are essential to increase the penetration depth and recovery rates. Spending additional time required for systematic downhole logging would be of great benefit to bridge the gaps between recovered cores and to tie the "floating" segments into the borehole stratigraphy. As a reliable drilling strategy is almost impossible to pursue at most sites on Antarctic shelves, due to likelihood of iceberg and massive sea-ice approach while on drill station, an extended contingency plan is essential for such a drilling campaign. This should include plenty of alternate sites and planning the additional use of gear for sampling (conventional coring) or surveying (bathymetry, seismics) that are complementary to the drilling objectives and can be used in the search for new sites if necessary. A ship's DP system with strong thrusters would certainly be of great advantage to improve the maneuverability in case of strong winds and small icebergs approaching. At least daily, or more frequent, updates of high-resolution satellite imagery are essential for iceberg and sea-ice drift observations and predictions, in addition to a bridge crew that is experienced in ice navigation and observation.

Acknowledgments
The operation of the MARUM-MeBo70 drill device was funded by the Alfred Wegener Institute through its Research Program PACES-II Topic 3 and grant AWI_PS104_001, the MARUM Center for Marine Environmental Sciences through the DFG funds EXC309/FZT15, the British Antarctic Survey through its Polar Science for Planet Earth program, and the UK IODP program. Every author was funded through one of these programs. We thank the master Stefan Schwarze and his crew of RV *Polarstern* for their excellent support during expedition PS104. We are also grateful to Kathrin Höppner of the German Aerospace Center (DLR) who provided us with daily updates of high-resolution radar images from the TerraSAR-X and TanDEM-X satellites, to Vanessa Bowman who helped in obtaining a first estimate on Cretaceous-Paleocene pollen ages. The helpful review comments by Julia Wellner and Carlota Escutia are greatly appreciated. This project contributes to the Scientific Committee on Antarctic Research (SCAR) Scientific Research Program *Past Antarctic Ice Sheet Dynamics* (PAIS). The MeBo70 core data will be made available in the World Data Center PANGAEA (https://www.pangaea.de/) after scientific analyses are published in subsequent papers.

References

Anderson, J. B., Warny, S., Askin, R. A., Wellner, J. S., Bohaty, S. M., Kirshner, A. E., . . . Majewski, W. (2011). Progressive Cenozoic cooling and the demise of Antarctica's last refugium. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 11356–11360. https://doi.org/10.1073/pnas.1014885108

Anderson, J. B., & Wellner, J. S. (Eds.). (2011). *Tectonic, climatic, and cryospheric evolution of the Antarctic Peninsula*. Washington, DC: American Geophysical Union. https://doi.org/10.1029/SP063

Anderson, J. B., Wellner, J. S., Wise, S., Bohaty, S., Manley, P., Smith, T., . . . Kulhanek, D. (2007). *Seismic and chronostratigraphic results from SHALDRIL II, northwestern Weddell Sea* (U.S. Geol. Surv. Open-File Rep. 2007-1047, 4 p.). https://doi.org/10.3133/of2007-1047.srp094

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

Backman, J., Moran, K., McInroy, D. B., & Mayer, L. A., and the Expedition 302 Scientists. (2006). *Proceedings of Integrated Ocean Drilling Program* (Vol. 302). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2204/iodp.proc.302.2006

Barker, P. F., Camerlenghi, A., Acton, G. D., Brachfeld, S. A., Cowan, E. A., Daniels, J., . . . Wolf-Welling, T. C. W. (1999). *Proceedings of Ocean Drilling Program Initial Report* (Vol. 178). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2973/odp.proc.ir.178.1999

Barker, P. E., Kennett, J. P., O'Connell, S., Berkowitz, S., Bryant, W. R., Burckle, L. H., . . . Wise, S. W. Jr. (1988). *Proceedings of Ocean Drilling Program Initial Report* (Vol. 113). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2973/odp.proc.ir.113.1988

Barnes, D. K. A., & Hillenbrand, C.-D. (2010). Faunal evidence for a late Quaternary trans-Antarctic seaway. *Global Change Biology*, *16*, 3297–3303. https://doi.org/10.1111/j.1365-2486.2010.02198.x

Barrett, P. J. (Ed.). (1989). *Antarctic Cenozoic history from CIROS-1 drillhole, western McMurdo sound* (Vol. 245, pp. 15–26). Wellington, New Zealand: DSIR Miscellaneous Bulletin.

Barron, J., Larsen, B., Baldauf, J., Alibert, C., Berkowitz, S., Caulet, J.-P., . . . Wei, W. (1989). *Proceedings of Ocean Drilling Program Initial Report* (Vol. 119). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2973/odp.proc.ir.119.1989

Bowman, V., Ineson, J., Riding, J., Crame, J., Francis, J., Condon, D., . . . Ferraccioli, F. (2016). The Paleocene of Antarctica: Dinoflagellate cyst biostratigraphy, chronostratigraphy and implications for the palaeo-Pacific margin of Gondwana. *Gondwana Research*, *38*, 132–148. https://doi.org/10.1016/j.gr.2015.10.018

Cape Roberts Science Team. (1999). Studies from the Cape Roberts project, Ross Sea, Antarctica, Initial report on CRP-2/2A. *Terra Antartica*, *6*, 1–173.

Cape Roberts Science Team. (2000). Studies from the Cape Roberts project, Ross Sea, Antarctica, Initial report on CRP-3. *Terra Antartica*, *7*, 1–209.

Escutia, C., Brinkhuis, H., & Klaus, A. and the Expedition 318 Scientists. (2011). *Proceedings of Ocean Drilling Program* (Vol. 318). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2204/iodp.proc.318.2011

Francis, J. E., & Poole, I. (2002). Cretaceous and early Tertiary climates of Antarctica: Evidence from fossil wood. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *182*, 47–64. https://doi.org/10.1016/S0031-0182(01)00452-7

Freudenthal, T., & Wefer, G. (2013). Drilling cores on the sea floor with the remote-controlled sea floor drilling rig MeBo. *Geoscientific Instrumentation, Methods and Data Systems*, *2*(2), 329–337. https://doi.org/10.5194/gi-2-329-2013

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. *Marine Geology*, *344*, 115–131. https://doi.org/10.1016/j.margeo.2013.06.011

Graham, A. G. C., Larter, R. D., Gohl, K., Dowdeswell, J. A., Hillenbrand, C.-D., Smith, J. A., . . . Kuhn, G. (2010). Flow and retreat of the Late Quaternary Pine Island-Thwaites palaeo-ice stream, West Antarctica. *Journal of Geophysical Research*, *115*, F03025. https://doi.org/10.1029/2009JF001482

Graham, A. G. C., Larter, R. D., Gohl, K., Hillenbrand, C.-D., Smith, J. A., & Kuhn, G. (2009). Bedform signature of a West Antarctic palaeo-ice stream reveals a multi-temporal record of flow and substrate control. *Quaternary Science Reviews*, *28*, 2774–2793. https://doi.org/10.1016/j.quascirev.2009.07.003

Hayes, D. E., and Frakes, L. A. (Eds.). (1975). *Deep sea drilling program preliminary report* (Vol. 28). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2973/dsdp.proc.28.1975

Hillenbrand, C.-D., Kuhn, G., Smith, J. A., Gohl, K., Graham, A. G. C., Larter, R. D., . . . Vaughan, D. G. (2013). Grounding-line retreat of the West Antarctic Ice Sheet from inner Pine Island Bay. *Geology*, *41*, 35–38. https://doi.org/10.1130/G33469.1

Hillenbrand, C.-D., Smith, J. A., Hodell, D. A., Greaves, M., Poole, C. R., Kender, S., . . . Kuhn, G. (2017). West Antarctic Ice Sheet retreat driven by Holocene warm water incursions. *Nature*, *547*, 43–48. https://doi.org/10.1038/nature22995

Hochmuth, K., & Gohl, K. (2013). Glaciomarine sedimentation dynamics of the Abbot glacial trough of the Amundsen Sea Embayment shelf, West Antarctica, In M. J. Hambrey, P. F. Barker, P. J. Barrett, et al. (Eds.), *Antarctic palaeoenvironments and earth-surface processes, Geological Society, London, Special Publications* (Vol. 381, pp. 233–244). London, UK: The Geological Society of London. https://doi.org/10.1144/SP381.21

Hollister, C. D., and Craddock, C. (Eds.). (1976). *Deep sea drilling program preliminary report* (Vol. 35). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2973/dsdp.proc.35.1976

Jakobsson, M., Anderson, J. B., Nitsche, F. O., Dowdeswell, J. A., Gyllencreutz, R., Kirchner, N., . . . Majewski, W. (2011). Geological record of ice shelf break-up and grounding line retreat, Pine Island Bay, West Antarctica. *Geology*, *39*, 691–694. https://doi.org/10.1130/G32153.1

Jenkins, A., Dutrieux, P., Jacobs, S., Steig, E. J., Gudmundsson, H., Smith, J. A., & Heywood, K. J. (2016). Ocean forcing and ice sheet response on decadal timescales: Lessons learnt from the Amundsen Sea Sector of Antarctica. *Oceanography*, *29*, 58–69. https://doi.org/10.5670/oceanog.2016.103

Kirshner, A., Anderson, J. B., Jakobsson, M., O'Regan, M., Majewski, W., & Nitsche, F. O. (2012). Post-LGM deglaciation in Pine Island Bay, West Antarctica. *Quaternary Science Reviews*, *38*, 11–26. https://doi.org/10.1016/j.quascirev.2012.01.017

Klages, J. P., Kuhn, G., Graham, A. G. C., Hillenbrand, C.-D., Smith, J. A., Nitsche, F. O., . . . Gohl, K. (2015). Palaeo-ice stream pathways and retreat style in the easternmost Amundsen Sea Embayment, West Antarctica, revealed by combined multibeam bathymetric and seismic data. *Geomorphology*, *245*, 207–222. https://doi.org/10.1016/j.geomorph.2015.05.020

Kristoffersen, Y., Strand, K., Vorren, T., Harwood, D., & Webb, P. (2000). Pilot shallow drilling on the continental shelf, Dronning Maud Land, Antarctica. *Antarctic Science*, *12*, 463–470. https://doi.org/10.1017/S0954102000000547

Kuhn, G., Hillenbrand, C.-D., Kasten, S., Smith, J. A., Nitsche, F. O., Frederichs, T., . . . Mogollón, J. M. (2017). Evidence for a palaeo-subglacial lake on the Antarctic continental shelf. *Nature Communications*, *8*, 15591. https://doi.org/10.1038/ncomms15591

Larter, R. D., Graham, A. G. C., Gohl, K., Kuhn, G., Hillenbrand, C.-D., Smith, J. A., . . . Schenke, H.-W. (2009). Subglacial bedforms reveal complex basal regime in a zone of paleo-ice stream convergence, Amundsen Sea Embayment, West Antarctica. *Geology*, *37*, 411–414. https://doi.org/10.1130/G25505A

Lowe, A. J., & Anderson, J. B. (2002). Reconstruction of the West Antarctic ice sheet in Pine Island Bay during the Last Glacial Maximum and its subsequent retreat history. *Quaternary Science Reviews*, *21*, 1879–1897. https://doi.org/10.1016/S0277-3791(02)00006-9

Minzoni, R. T., Majewski, W., Anderson, J. B., Yokoyama, Y., Fernandez, R., & Jakobsson, M. (2017). Oceanographic influences on the stability of the Cosgrove Ice Shelf, Antarctica. *The Holocene*, *27*(11), 1645–1658. https://doi.org/10.1177/0959683617702226

Mohtadi, M., Bergenthal, M., Contreras, A., Dang, H., Düßmann, R., Freudenthal, T., . . . Weiner, A. (2012). Report and preliminary results of RV Sonne cruise SO 221 INVERS, Hong Kong-Hong Kong, 17.05.2012–07.06.2012. In *Berichte aus dem Fachbereich Geowissenschaften der Universität Bremen* (Vol. 288). Bremen, Hannover: Department of Geosciences, University of Bremen. http://nbn-resolving.de/urn:nbn:de:gbv:46-00102735-15

Moncrieff, A. C. M., & Kelly, S. R. A. (1993). Lithostratigraphy of the uppermost Fossil Bluff Group (early cretaceous) of Alexander Island, Antarctica: History of an Albian regression. *Cretaceous Research*, *14*, 1–15. https://doi.org/10.1006/cres.1993.1001

Muto, A., Peters, L. E., Gohl, K., Sasgen, I., Alley, R. B., Anandakrishnan, S., & Riverman, K. L. (2016). Subglacial bathymetry and sediment distribution beneath Pine Island Glacier ice shelf modeled using aerogravity and in situ geophysical data: New results. *Earth and Planetary Science Letters*, *433*, 63–75. https://doi.org/10.1016/j.epsl.2015.10.037

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., . . . Williams, T. (2009). Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature*, *458*, 322–328. https://doi.org/10.1038/nature07867

Nitsche, F. O., Gohl, K., Larter, R. D., Hillenbrand, C.-D., Kuhn, G., Smith, J. A., . . . Jakobsson, M. (2013). Paleo ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica. *The Cryosphere*, *7*, 249–262. https://doi.org/10.5194/tc-7–249-2013

Nitsche, F. O., Jacobs, S. S., Larter, R. D., & Gohl, K. (2007). Bathymetry of the Amundsen Sea continental shelf: Implications for geology, oceanography, and glaciology. *Geochemistry, Geophysics, Geosystems*, *8*, Q10009. https://doi.org/10010.11029/12007GC001694

O'Brien, P. E., Cooper, A. K., Richter, C., Barr, S. R., Bohaty, S. M., Claypool, G. E., . . .Williams, T. (2001). *Proceedings of Ocean Drilling Program Initial Report* (Vol. 188). Washington, DC: U.S. Government Printing Office. https://doi.org/10.2973/odp.proc.ir.188.2001

Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., van den Broeke, M. R., & Padman, L. (2012). Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature*, *484*, 502–505. https://doi.org/10.1038/nature10968

Scambos, T. A., Bell, R. E., Alley, R. B., Anandakrishnan, S., Bromwich, D. H., Brunt, K., . . . Yager, P. (2017). How much, how fast? A science review and outlook for research on the instability of Antarctica's Thwaites Glacier in the 21st century. *Global and Planetary Change*, *153*, 16–34. https://doi.org/10.1016/j.gloplacha.2017.04.008

Scherer, R. P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H., & Kamb, B. (1998). Pleistocene collapse of the West Antarctic Ice Sheet. *Science*, *281*, 82–85. https://doi.org/10.1126/science.281.5373.82

Smith, J. A., Andersen, T. J., Shortt, M., Truffer, M., Stanton, T. P., Bindschadler, R., . . . Vaughan, D. G. (2017). Sub-ice-shelf sediments record history of 20th century retreat of Pine Island Glacier. *Nature*, *541*, 77–80. https://doi.org/10.1038/nature20136

Smith, J. A., Hillenbrand, C.-D., Kuhn, G., Klages, J. P., Graham, A. G. C., Larter, R. D., . . . Frederichs, T. (2014). New constraints on the timing of West Antarctic Ice Sheet retreat in the eastern Amundsen Sea since the Last Glacial Maximum. *Global and Planetary Change*, *122*, 224–237. https://doi.org/10.1016/j.gloplacha.2014.07.015

Smith, J. A., Hillenbrand, C.-D., Kuhn, G., Larter, R. D., Graham, A. G. C., Ehrmann, W., . . . Forwick, M. (2011). Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment. *Quaternary Science Reviews*, *30*, 488–505. https://doi.org/10.1016/j.quascirev.2010.11.020

Turner, J., Orr, A., Gudmundsson, G. H., Jenkins, A., Bingham, R. G., Hillenbrand, C.-D., & Bracegirdle, T. J. (2017). Atmosphere-ocean-ice interactions in the Amundsen Sea Embayment, West Antarctica. *Reviews of Geophysics*, *55*, 235–276. https://doi.org/10.1002/2016RG000532

Wellner, J. S., Anderson, J. B., & Wise, S. W. (2005). The inaugural SHALDRIL expedition to the Weddell Sea. *Scientific Drilling*, *1*, 40–43. https://doi.org/10.5194/sd-1-40-2005

Zinsmeister, W. J. (1982). Review of the Upper Cretaceous-Lower Tertiary sequence on Seymour Island, Antarctica. *Journal of the Geological Society*, *139*, 779–785. https://doi.org/10.1144/gsjgs.139.6.0779