THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY
Oceanography

CITATION

Escutia, C., R.M. DeConto, R. Dunbar, L. De Santis, A. Shevenell, and T. Naish. 2019. Keeping an eye on Antarctic Ice Sheet stability. *Oceanography* 32(1):32–46, https://doi.org/10.5670/oceanog.2019.117.

DOI

https://doi.org/10.5670/oceanog.2019.117

Keeping an Eye on Antarctic Ice Sheet Stability

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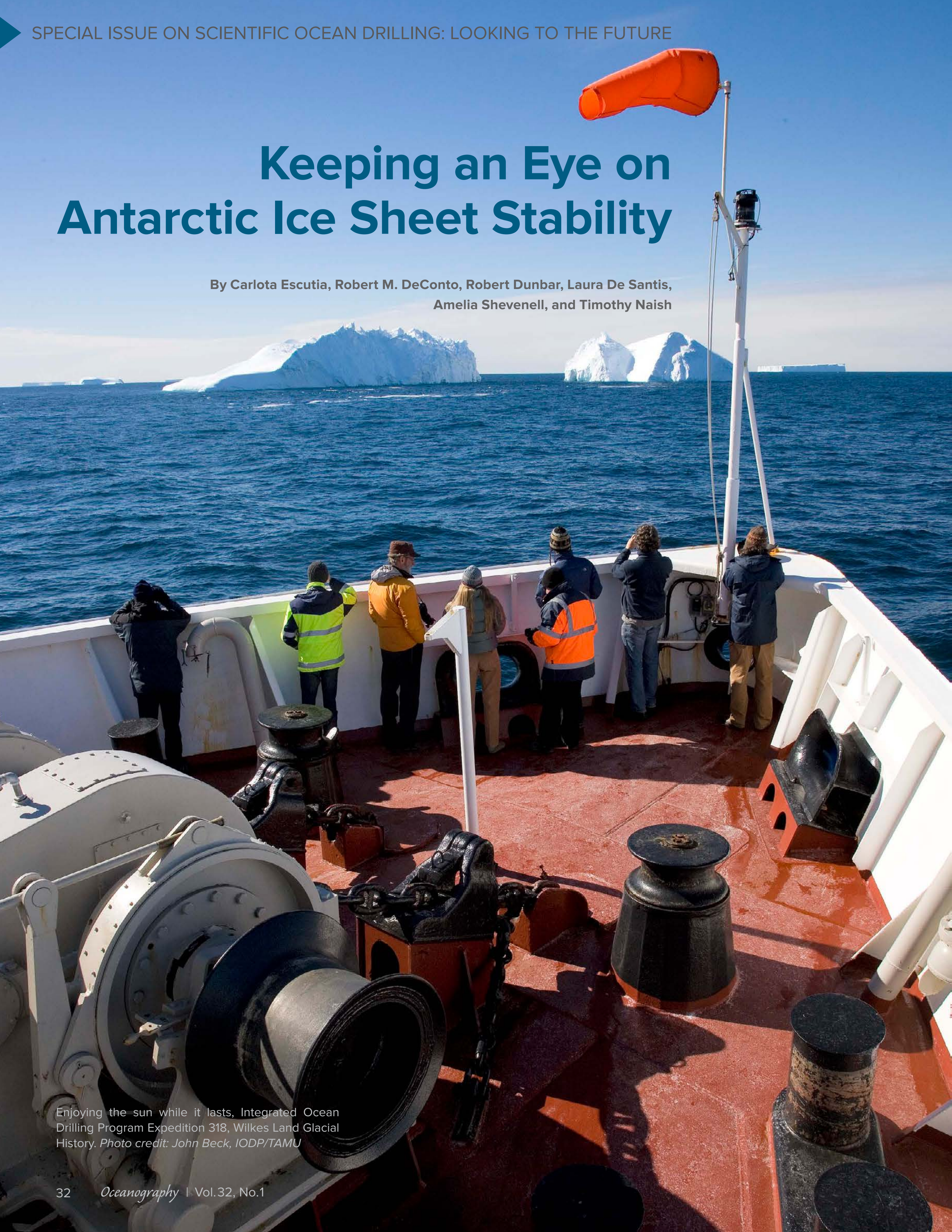

Enjoying the sun while it lasts, Integrated Ocean Drilling Program Expedition 318, Wilkes Land Glacial History. *Photo credit: John Beck, IODP/TAMU*

ABSTRACT. Knowledge of how the Antarctic Ice Sheet (AIS) responded in the geologic past to warming climates will provide powerful insight into its poorly understood role in future global sea level change. Study of past natural climate changes allows us to determine the sensitivity of the AIS to higher-than-present atmospheric carbon dioxide (CO_2) concentrations and global temperatures, thereby providing the opportunity to improve the skill and performance of ice sheet models used for Intergovernmental Panel on Climate Change (IPCC) future projections.

Antarctic and Southern Ocean (south of 60°S latitude) marine sediment records obtained over the last 50 years by seven scientific ocean drilling expeditions have revolutionized our understanding of Earth's climate system and the evolution and dynamics of the Antarctic ice sheets through the Cenozoic (0–65 million years ago). These records document an ice-free subtropical Antarctica between ~52 and 40 million years ago when CO_2 was ~1,000 ppm; the initiation of continental-scale Antarctic ice sheets ~34 million years ago as CO_2 dropped below 800 ppm; evidence for a dynamic, largely terrestrial, ice sheet driving global sea level changes of up to 40 m amplitude between 34 and 15 million years ago; and colder periods of highly dynamic, marine-based ice sheets contributing up to 20 m of global sea level rise when CO_2 levels were in the range of 500–300 ppm between ~14 and 3 million years ago.

Notwithstanding these discoveries, paleoenvironmental records obtained around Antarctica are still limited in their geographical coverage and do not provide a basis for comprehensive understanding of how different sectors of Antarctica respond to climate perturbations. Transects of drill cores spanning ice-proximal to ice-distal environments across the continental margin and at sensitive locations that have been identified by models and recent observations are needed to fully understand temporal and spatial ice volume changes that result from complex ice sheet-ocean-atmosphere interactions. These records are also critical for reconstructing equator-to-pole temperature gradients through time to better understand global climate change, interhemispheric long-distance transmission of changes through the atmosphere and ocean (teleconnections), and the amplification of climate signals in the polar regions.

Future Antarctic scientific ocean drilling will remain key to obtaining records of past Antarctic Ice Sheet dynamics that can be integrated into coupled ice sheet-climate models for improved projections of sea level change. Thus, keeping an eye on ice sheet stability is critical for improving the accuracy and precision of predictions of future changes in global and regional temperatures and sea level rise.

INTRODUCTION

The Antarctic cryosphere and the Southern Ocean are key components of Earth's climate system. By influencing Earth's average albedo, sea ice extent, atmospheric and oceanic circulation, marine nutrient distribution, and global sea level, the growth and decay of Antarctic ice sheets plays an important role in regional and global climate. Moreover, it has been estimated that the full melting of all Antarctic ice has a sea level equivalent (SLE) of ~58 m (Fretwell et al., 2013). Despite the critical role of Antarctica and the Southern Ocean in the global climate system, our understanding of ice-ocean-atmosphere interactions that control the dynamics and stability of the ice sheets is still rudimentary, lacking in fundamental knowledge required for confident predictions of future change. To improve understanding of the role Antarctica and the Southern Ocean play in Earth's climate system and global sea level, it is essential to have a more complete understanding of the region's past climate variability, the ensuing responses of the ice sheet, and the hemispheric and global consequences. However, key geological and geophysical data from the Antarctic region have not yet been obtained due in part to the remoteness and inaccessibility of the Antarctic continent. Also, because Antarctica's massive ice sheets cover all but 0.18% of the continent, terrestrial records, which provide valuable snapshots into past climate conditions and ice sheet dynamics, are geographically sparse, difficult to obtain, and also problematic as they lack accurate age controls.

Scientific ocean drilling of the more accessible marine sedimentary archives around the Antarctic continental margin has revolutionized our understanding of Earth's climate system through the Cenozoic (0–65 million years ago [Ma]). These sediment cores illuminate an ancient history in which Antarctica was subtropical and ice-free, allow determination of the onset of the continental-scale Antarctic ice sheets, provide long detailed orbitally paced records of ice advances and retreats, and offer insight into the ice sheets' stability thresholds and contributions to global sea level. This knowledge has been acquired by seven scientific ocean drilling expeditions conducted south of 60°S latitude since the Deep Sea Drilling Project (DSDP) began operations in 1968 (Figure 1). In addition, valuable coastal and marine sedimentary sections from the Ross Sea, the Antarctic Peninsula, and the Amundsen Sea regions (Figure 1) have been recovered by other scientific ocean drilling programs (i.e., the international Cenozoic Investigation in the Western Ross Sea [CIROS] project, the Cape Roberts Project [CRP], the ANtarctic geological DRILLing [ANDRILL] project, the US SHALlow DRILling [SHALDRIL] project, and work with the German Meeresboden-Bohrgerät [MeBo] drilling rig). However, even taken together, existing drill core coverage remains extremely sparse relative to the large size of the Antarctic continent (i.e., 14 million square kilometers, about twice the size of Australia) and the geological complexity of Antarctica and its ice sheets. Most drill sites track either ice-proximal (coastal/shelf) or ice-distal conditions, but rarely both, and many sectors of the Antarctic margin have yet to be drilled (Figure 1). As a result, critical questions regarding

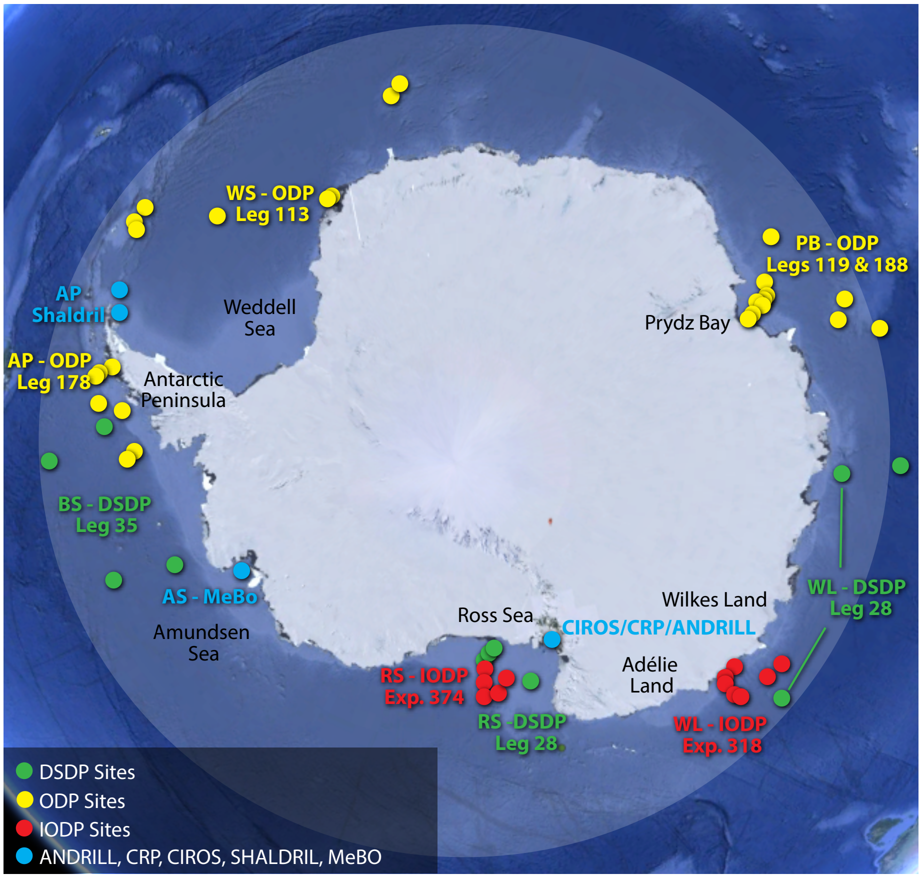

FIGURE 1. Map showing the drill site locations of the seven scientific ocean drilling expeditions (DSDP/ODP/IODP) undertaken around Antarctica and the Southern Ocean south of 60°S (within the lighter shaded circle) since 1973. Also indicated are the locations of expeditions by other scientific drilling programs (blue dots): the international Cenozoic history of the Ross Sea (CIROS) Project, Cape Roberts Project (CRP), and ANDRILL Programs, all in the Ross Sea; the US SHALDRIL program around the Antarctic Peninsula (AP); and the German MeBo drilling in the Admunsen Sea (AS). Deep Sea Drilling Project (DSDP) sites appear in green, Ocean Drilling Program (ODP) sites in yellow, and Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) sites in red. WL = Wilkes Land. RS = Ross Sea. PB = Prydz Bay. BS = Bellinghausen Sea. WS = Weddell Sea.

the nature, cause, timing, and rate of processes involved in the growth and decay of the Antarctic Ice Sheet (AIS) remain.

Significant gaps persist in our knowledge of past climate, ocean, and ice sheet dynamics over a variety of timescales. Ice core records of Earth's past atmospheric characteristics are one of the most valuable climate recorders, revealing that carbon dioxide levels today are the highest over the last 800,000 years. Ice-proximal marine sedimentary records are needed to provide paleoclimate and ice sheet dynamics records that overlap the ice core records, but then extend back millions of years, to times when temperatures and CO_2 concentrations were like those projected by the IPCC (2014) within this century and beyond. Future Antarctic scientific ocean drilling will remain key to obtaining records of past Antarctic ice sheet dynamics that can be integrated into coupled ice sheet-climate models. Both improving and expanding those models is critical for improving the accuracy and precision of predictions of future changes in global and regional temperatures and sea level rise.

MARINE RECORDS OF ANTARCTIC ICE SHEET HISTORY AND DYNAMICS

Prior to the first scientific ocean drilling of the Antarctic continental margin in 1973, the prevailing hypothesis was that Antarctica had glaciated at the onset of the Pleistocene (~2.6 Ma). In 1973, DSDP Leg 28 accomplished the first scientific ocean drilling in two areas of the Antarctic margin, the Wilkes Land abyssal plain and the Ross Sea continental margin (Figure 1). Leg 28 provided the first physical evidence for glaciation extending back at least to the late Oligocene (~25 Ma; Hayes et al., 1975). Sediments also recorded an increase in ice volume around 14 Ma, interpreted to represent the development of a largely stable East Antarctic Ice Sheet (EAIS; Kennett et al., 1975; Kennett and Shackleton, 1975).

The oxygen isotope ($\delta^{18}O$) record of foraminifers from sediments collected in the southwest Pacific (about 48°–52°S) during DSDP Leg 29 indicated that mean annual temperatures at these latitudes were near freezing in the early Oligocene, conditions under which Antarctic glaciers would descend to sea level and sea ice would expand (Shackleton and Kennett, 1975). This led to the hypothesis that the tectonic separation of South America and Australia from Antarctica resulted in the development of the Antarctic Circumpolar Current (ACC), which thermally isolated Antarctica and encouraged ice sheet development (Kennett, 1977). This hypothesis remained the leading paradigm for Antarctic ice growth until ice sheet numerical model simulations revealed that a threshold in declining atmospheric CO_2 concentrations may have exerted a larger first-order control on Antarctica's ice sheets (DeConto and Pollard, 2003).

After 1973, 13 years passed before the successor to DSDP, the Ocean Drilling Program (ODP; 1983–2003), returned to Antarctica for drilling during Legs 113 and 119 in the Weddell Sea and Prydz Bay, respectively. The goal of these legs was to determine Antarctica's glacial history in different sectors of the continent. The Antarctic Earth science drilling community quickly realized that remoteness and challenging weather and ice conditions around the continent, coupled with proposal pressure to drill in other areas of the globe, placed scientific drilling in

Antarctica on a long time cycle, with several decade(s) between major drilling programs. This infrequency in Antarctic research campaigns has impeded the timely acquisition of new knowledge about the initiation, evolution, and stability of the Antarctic ice sheets and related sea level changes. In fact, most knowledge of ice sheet and sea level history came from indirect ice volume and temperature estimates derived from lower latitude foraminifer isotopic stratigraphy and sea level reconstructions from low-latitude passive continental margins (e.g., Zachos et al., 2001a; Miller et al., 2012). To address the limitations associated with inferences from far-field data sets, the Antarctic science community, guided by ice sheet models and existing direct records from the Antarctic margin, has been developing and promoting coordinated plans for drilling around the Antarctic margin since the 1990s.

The first coordinated set of drilling proposals under SCAR-ANTOSTRAT (Scientific Committee for Antarctic Research-Antarctic Offshore Seismic Stratigraphy) aimed to derive the history of the ice sheet and to understand terrigenous sediment glacial transport and deposition under a glacial regime (Barker et al., 1998). ANTOSTRAT brought together research groups responsible for collecting offshore geological and geophysical data to collaborate in studies of Cenozoic paleoenvironments and to promote scientific ocean drilling around Antarctica (Cooper and Webb, 1992). ANTOSTRAT followed the Madrid Protocol on Antarctic Environmental Protection to the Antarctic Treaty (ATCM, Antarctic Treaty System, 1991), which established a 50-year moratorium on resource exploration and exploitation. Under the auspices of the ATCM (Recommendation XVI-12), the Antarctic Seismic Data Library System (SDLS) for Cooperative Research was formalized as a model for collaboration and equitable sharing of Antarctic multichannel seismic reflection data for geoscience studies.

The ANTOSTRAT project, with crucial SDLS support, established the groundwork for circum-Antarctic seismic, drilling, and rock coring programs designed to decipher Antarctica's tectonic, stratigraphic, and climate histories. Using data from the SDLS, scientists involved in the ANTOSTRAT project developed a strategy for drilling continental shelf-to-rise transects at key sites around Antarctica based on data from numerical models of ice sheet behavior (e.g., Huybrechts, 1993; Barker et al., 1998). The strategy required direct sampling of both continental shelf sediments and the more continuous and easily age-dated sediments of the continental rise (Figure 2). Shelf sediments are typically discontinuous and harder to date because of erosion by the advances and retreats of the ice sheet across the shelf as well as issues regarding recovery of glacial deposits during drilling. Nevertheless, preserved shelf sediments are the only direct records of variability in the extent of the ice sheet, because they can reveal the grounding line (or maximum extent of) ice sheet advances and retreats. Continental shelf records can be coupled with less direct but more continuous and better-dated continental rise records of glacial-interglacial cycles and related paleoceanographic changes (Figure 2). Data from the two types of settings can be then combined and used for providing new scientific ocean drilling targets through numerical ice sheet models. Of the five key regions identified by ANTOSTRAT (Barker et al., 1998), two were drilled during ODP Legs 178 and 188 west of the Antarctic Peninsula and in Prydz Bay, respectively (Figure 1).

Between 2000, when ODP Leg 188 drilled in Prydz Bay, and 2010, when Integrated Ocean Drilling Program (IODP) Expedition 318 drilled along the Wilkes Land margin, scientific priorities within the Antarctic community had evolved under the umbrella of two SCAR research programs that succeeded ANTOSTRAT: the international Antarctic Climate Evolution (ACE) and the Past Antarctic Ice Sheet (PAIS) programs. With these two new programs, scientists sought to advance confidence

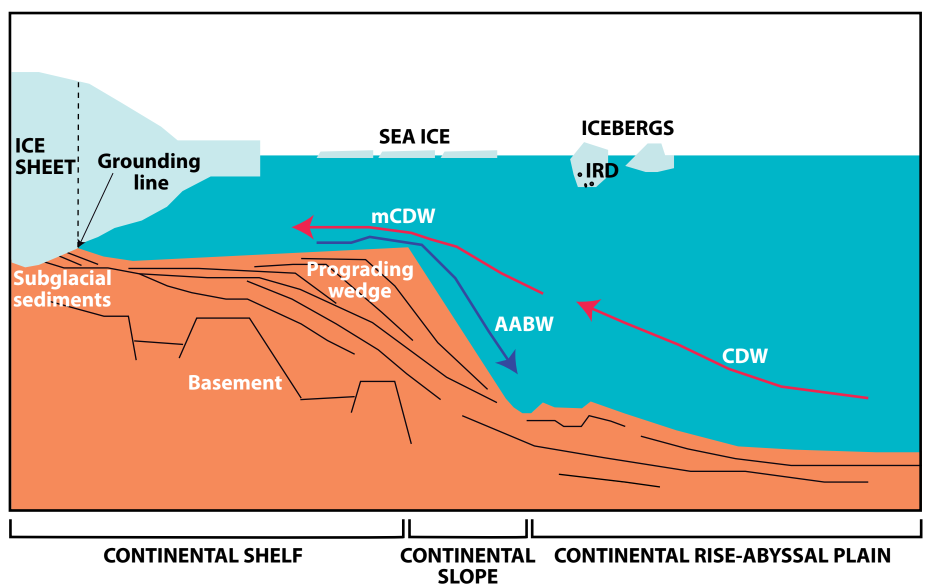

FIGURE 2. Conceptual cross section across the Antarctic margin. Subglacial to ice-proximal (coastal-shelf) to ice-distal depositional environments that contain the sedimentary record of past ice sheet dynamics result from changing atmosphere-ice sheet-ocean interactions. The figure also shows various components of a polar margin referred to in the text (i.e., grounding line, subglacial sediments, etc.). Oceanic processes in this sketch represent a two-dimensional snapshot showing enhanced modified Circumpolar Deep Water (mCDW) intrusion across the continental shelf. However, intrusion positions shift with the positions of the westerlies during glacial and interglacial cycles. AABW = Antarctic Bottom Water. IRD = Ice-rafted debris.

in predictions of ice sheet and sea level responses to future climate and ocean warming by improving understanding of the sensitivity of the Antarctic ice sheets to a broad range of past climatic and oceanic conditions. Both programs highlighted the need to integrate geological reconstructions of past ice sheet behavior with numerical ice sheet modeling. Consequently, drilling programs were designed to target areas of the Antarctic margin shown by the models to be most sensitive to climate change, in most cases, in areas where the ice sheet is grounded on land that lies below sea level (i.e., marine-based; Figure 3). These drilling programs targeted study of specific intervals and events, including past "greenhouse" climates warmer than today, and more recent episodes of warming and ice sheet retreat during glacial terminations. In addition, programs were developed to collect cores along depth and latitudinal transects to provide information about ice sheet-ocean interactions, which play a critical role in the current ice sheet mass imbalance (e.g., Shepherd et al., 2018; Rignot et al., 2019). A coordinated plan was developed to expand the existing core coverage with near-coastal drill targets complementing existing deep-water sites, and vice versa, and with the goal of targeting unsampled areas of the Antarctic margin. IODP Expedition 318 (January–March 2010) drilled one unexplored margin of East Antarctica, the eastern Wilkes-Adélie Land (Escutia et al., 2011, 2014). Eight years later, this expedition was followed by International Ocean Discovery Program (IODP) Expedition 374 (January–March 2018) to the Ross Sea (McKay et al., 2018). Two additional drilling expeditions are being carried out in early 2019 to increase drilling coverage of the Antarctic continental margins, IODP Expedition 379 to the Amundsen Sea and IODP Expedition 382 to the Scotia Sea (Figures 1 and 4).

Geological records obtained by scientific ocean drilling around the Antarctic continental margin have been key for providing boundary conditions and simulation targets, albeit localized, that greatly help calibration of the ice sheet models used to simulate future Antarctic contributions to global mean sea level for IPCC representative concentration pathways (Golledge et al., 2015; DeConto and Pollard, 2016). It is beyond the scope of this paper to outline in detail the findings of each one of the scientific ocean drilling expeditions in Antarctica; instead, we highlight some of the most relevant advances and contributions to our knowledge of greenhouse conditions, past Antarctic ice sheet dynamics and stability, and their relations to oceanographic and sea level changes.

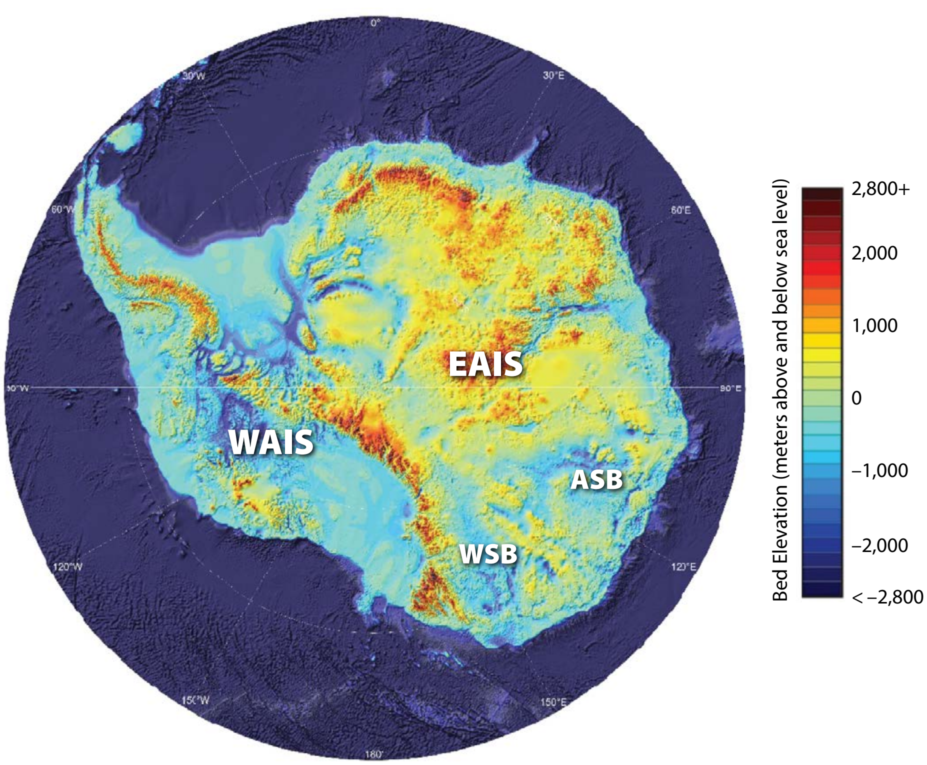

FIGURE 3. A BEDMAP 2 image, representing ice bed, surface, and thickness data sets, shows the locations where the bedrock on which the West Antarctic Ice Sheet (WAIS) and East Antarctic Ice Sheet (EAIS) rest is well below sea level. Two major subglacial basins referred to in the text are also labeled: the Wilkes Subglacial Basin (WSB) and the Aurora Subglacial Basin (ASB). *Modified from Fretwell et al. (2013)*

ADVANCES IN OUR KNOWLEDGE OF ANTARCTIC ICE SHEET DYNAMICS

Eocene Peak Greenhouse Conditions and Climate Deterioration

The warmest global climates of the past 65 million years occurred during the early Eocene epoch (about 56–4 Ma). Atmospheric carbon dioxide levels were in excess of one thousand parts per million by volume (>1,000 ppmv), which is within the range of IPCC projections for Earth's atmosphere over the next several centuries (Foster et al., 2017; Figure 5). Geological data from this period are therefore relevant to the response of Earth's ice sheets, climate, and biosphere to the high atmospheric carbon dioxide levels that are expected with unabated anthropogenic warming. However, these early Paleogene analogues of future climates are not necessarily straightforward comparisons, because climate system boundary conditions (e.g., plate tectonic configurations, ocean circulation) in addition to CO_2 have changed.

Sediments recovered in the Weddell Sea during ODP Leg 113 (December 1986 to March 1987) record cool subtropical climates, with average surface and deepwater temperatures between 16°C and 9°C in the early Eocene (Stott et al., 1990; Kennett and Stott, 1990). More than two decades later, biotic indicators (pollen, spores) and organic geochemical paleothermometers (bacterial branched tetraether lipids employed to indicate terrestrial paleotemperature) in sediments obtained during IODP Expedition 318 on the Wilkes-Adélie Land margin have yielded continental temperature reconstructions for this sector of the east Antarctic margin during peak greenhouse conditions ~55 Ma (Pross et al., 2012; Contreras et al., 2013). These temperatures suggest cold monthly mean temperatures >10°C, with the coldest estimates from organic geochemical paleothermometers of 24°–27°C. Paleogeographic reconstructions show the Wilkes Land coast to be already positioned at a high paleolatitude of about 70°S during the early Eocene (Pross et al., 2012). The recorded temperatures therefore suggested dramatically greater high-latitude warming than previously simulated by models of the Eocene greenhouse climates. These findings required additional modeling to identify the forcing and feedback mechanisms needed to maintain the higher degree and range of temperatures reconstructed from these sedimentary proxy records. Reconciliation of the mismatch between model and data temperature estimates requires some combination of very strong radiative forcing during the Eocene compared with modern conditions and/or enhanced climate sensitivity due to strong positive feedbacks (Caballero and Huber, 2013).

A 20 million year cooling trend followed the Early Eocene Climatic Optimum (Figure 5). In the Weddell Sea, ocean temperatures cooled from around 20°C to 8°C by the middle Eocene (45 Ma; Stott et al., 1990; Kennett and Stott, 1990). In Prydz Bay, cool environments were reported from shelf sediments recovered by ODP Leg 188 (Cooper et al., 2004). Along the Wilkes-Adélie Land margin, biotic indicators in sediments record a change to a temperate rainforest biome, implying a decline of around 2°–3°C in temperature from the early to the middle Eocene, with organic geochemical paleotemperature proxies suggesting the coolest temperatures to range from 17°–20°C (Pross et al., 2012; Contreras et al., 2013). This cooling has been postulated to coincide with cold waters from the Ross Sea Gyre flowing through the incipient opening of the southern Tasman Gateway, implying that the tectonic opening of this gateway provided a mechanism for cooling along the eastern Wilkes-Adélie Land margin following the Early Eocene Climatic Optimum (Bijl et al., 2013). These results imply that although atmospheric CO_2 forcing alone might provide uniform middle Eocene cooling, the early opening of the Tasman Gateway is more consistent with Southern Ocean surface water and global deep ocean cooling in the apparent absence of (sub-) equatorial cooling (Bijl et al., 2013).

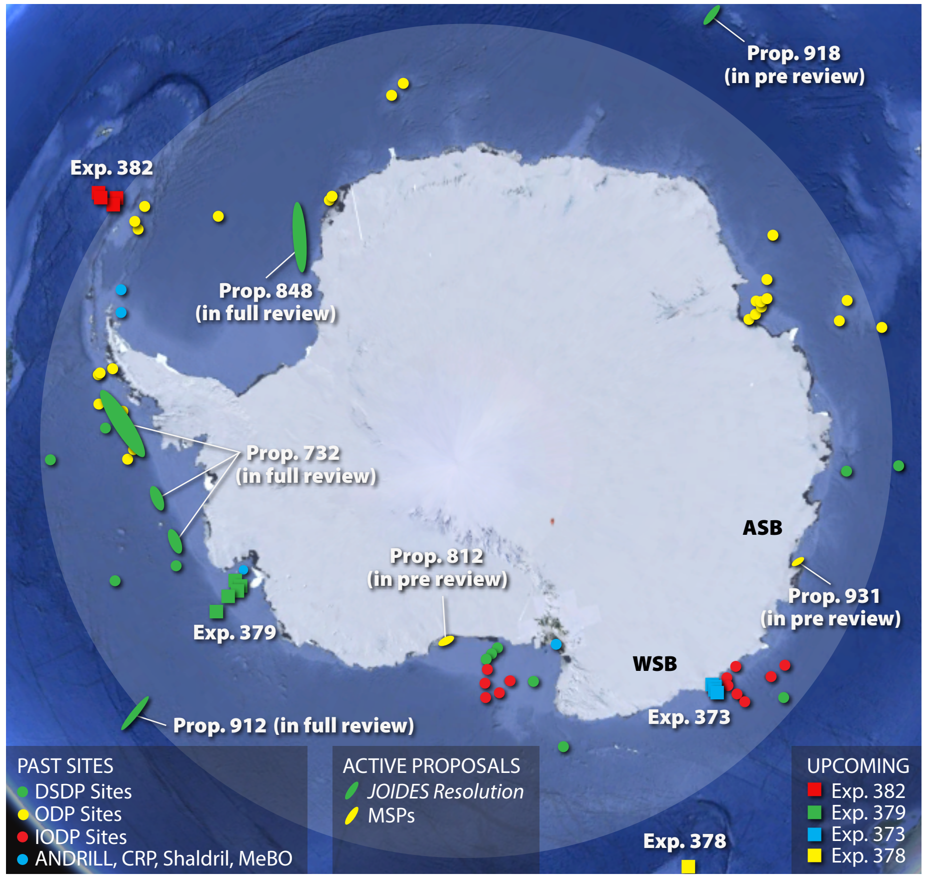

FIGURE 4. Past and future scientific ocean drilling sites around Antarctica. Past sites are marked by colored circles. Green ellipses are regions targeted in active proposals to be drilled with *JOIDES Resolution*, and yellow ellipses indicate regions targeted to be drilled with mission-specific platforms (MSP); three proposals are in "pre" review and three are in "full" review. Scheduled expeditions are marked by colored squares: Expedition 379-Amundsen Sea (green, JOIDES Resolution), Expedition 382-Iceberg Alley (red, JOIDES Resolution), and Expedition 373-Cenozoic Paleoclimate (blue, mission-specific platform). Expedition 378-South Pacific Paleogene Climate (yellow square) has been delayed. ASB = Aurora Subglacial Basin. WSB = Wilkes Subglacial Basin.

The Eocene-Oligocene Climate Transition and the Establishment of a Continent-Wide Ice Sheet in Antarctica

The Eocene warmth was followed by cooling, declining atmospheric CO_2 (Figure 5), and concurrent tectonic reorganizations that culminated in continental-scale glaciation of Antarctica at around 34 Ma (the Eocene-Oligocene transition; EOT). DSDP Leg 28 drilling in the eastern Ross Sea continental shelf was first to recover diamicts (ice-proximal glacial deposits), evidence that grounded ice from the West Antarctic Ice Sheet

(WAIS) first developed around 25 Ma (Hayes et al., 1975). Subsequent drilling from sea ice platforms (CIROS and CRP projects) revealed slightly older AIS glacial expansion in the earliest Oligocene (Barrett, 1989, 2007) that was restricted to the continent and was highly responsive to orbital forcing (Galleoti et al., 2016). Hints to the continental size of this first Antarctic ice sheet came from drilling of the Weddell Sea continental slope during ODP Leg 113. Ice-distal sediments suggested the presence of an East Antarctic Ice Sheet (EAIS) in this margin by at least the earliest Oligocene, based on evidence of the formation of cold deep waters and indirect indicators (i.e., ice rafted debris delivered by icebergs; Barker et al., 1988). ODP Leg 119 in Prydz Bay (December 1987 to February 1988) was, however, the first to recover diamicts from the east Antarctic continental shelf, providing direct evidence that the EAIS was delivering ice to the shelf edge since at least the early Oligocene (Barron et al., 1991; Hambrey et al., 1991). ODP Leg 188 recovered sediments from the shelf dating the arrival of ice sheets to the Prydz Bay continental shelf by 35 Ma (O'Brien et al., 2001; Cooper et al., 2004). A decade later, IODP Expedition 318 continental shelf diamicts and continental rise sediments also revealed the existence of an ice sheet on the Wilkes-Adélie Land sector of the east Antarctic margin by the earliest Oligocene (33.6 Ma, the Oi-1 event; Miller et al., 1991; Escutia et al., 2011, 2014). Sediments from this margin also indicated that ice growth was associated with a major restructuring of the Southern Ocean plankton ecosystem with the establishment of high seasonal primary productivity in a cooler environment and place where seasonal sea ice developed (Houben et al., 2013).

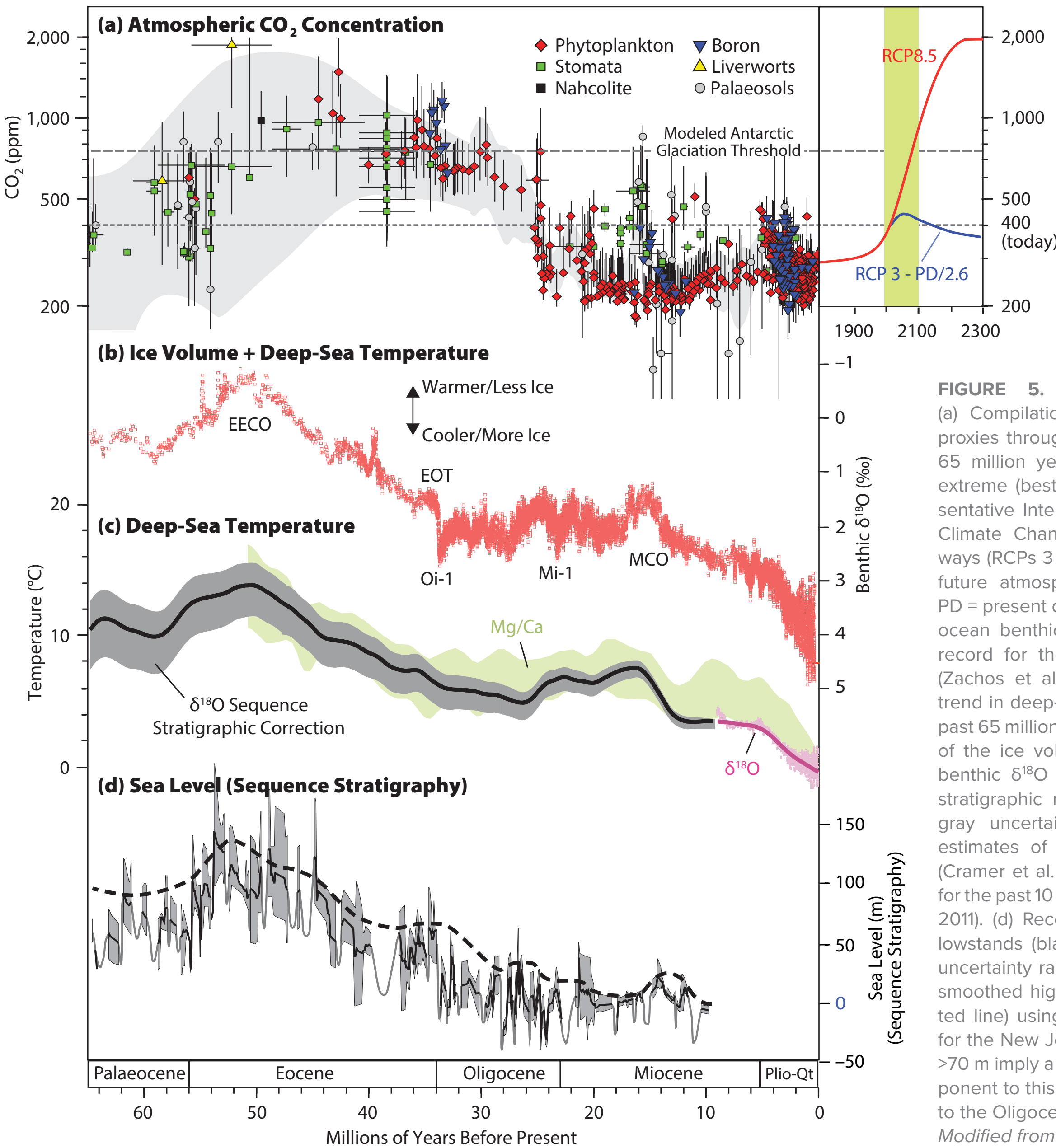

FIGURE 5. Data reconstructions: (a) Compilation of atmospheric CO_2 proxies throughout the Cenozoic (last 65 million years; left side). The two extreme (best and worst case) representative Intergovernmental Panel on Climate Change concentration pathways (RCPs 3 and 8.5) for historic and future atmospheric CO_2 (right side). PD = present day. (b) Composite deep-ocean benthic oxygen isotope ($\delta^{18}O$) record for the last 65 million years (Zachos et al., 2001a). (c) Long-term trend in deep-sea temperature for the past 65 million years based on removal of the ice volume component of the benthic $\delta^{18}O$ record using sequence stratigraphic records (black line with gray uncertainty band) and Mg/Ca estimates of deep-sea temperatures (Cramer et al., 2009) and scaled $\delta^{18}O$ for the past 10 million years (Miller et al., 2011). (d) Reconstruction of sea level lowstands (black lines) with minimum uncertainty ranges (gray shading) and smoothed highstand trend (black dotted line) using sequence stratigraphy for the New Jersey margin. Sea levels >70 m imply a significant tectonic component to this record, particularly prior to the Oligocene (Kominz et al., 2008). *Modified from McKay et al. (2015)*

The role of Earth deformation processes on near-field (i.e., close to the Antarctic continent) sea level changes and ice sheet dynamics was established through the integration of geological data from three Antarctic margins (Wilkes-Adélie Land, IODP Expedition 318; Prydz Bay, ODP Leg 188; and the Ross Sea, CRP) with models that couple ice sheet and glacial isostatic adjustment (GIA) (Stocchi et al., 2013). These data-model comparisons suggest that the growth of a continent-wide Antarctic ice sheet by the earliest Oligocene (33.6 Ma) induced crustal deformation and significant gravitational perturbations around the continent as water mass was transferred from the ocean and "piled up" in the ice sheets. These perturbations resulted in a complex spatial pattern of relative sea level change different from the expected eustatic signal, whereby sea level is rising instead of falling near the continent (Stocchi et al., 2013). These results highlight the relevance of local sea level change influencing the equilibrium state of an ice sheet grounding line, and with that the stability of local/regional ice sheets.

Ice Sheet Dynamics Under Warmer-than-Present Climates of the Icehouse World

Earliest Oligocene to Holocene sediments recovered from Antarctica's continental margins provide insights into the control exerted by changes in atmospheric CO_2 concentrations and Earth's geodynamic processes on the extent and volume of the AIS over long periods of time. In addition, these sedimentary records show that multiple systematic oscillations of Antarctica's ice sheets (i.e., advances-retreats of the AIS during glacial-interglacial cycles, respectively) have been strongly influenced by Earth's astronomical variations (i.e., Milankovitch cycles). Here, we summarize some of the most recent advances related to the behavior of the Antarctic ice sheets under warmer-than-present climates, including potential thresholds for changes in their behavior.

During the Oligocene (33.9–23.03 Ma) and Miocene (23.03-5.3 Ma), atmospheric CO_2 concentrations ranged between 400 ppmv and 650 ppmv (Figure 5; Foster et al., 2012; Badger et al., 2013; Zhang et al., 2016). Foster and Rohling (2013) inferred that within these atmospheric concentrations, global ice sheets were likely insensitive to climate change. In contrast, variability in the deep-sea benthic foraminiferal oxygen isotope ($\delta^{18}O$) records suggests that Antarctic ice volumes fluctuated considerably and were paced dominantly by the 100–400 thousand year (ka) orbital cycles (e.g., Pälike et al., 2006; Holbourn et al., 2007; Liebrand et al., 2011; Beddow et al., 2016). This latter observation is supported by drill cores from the Ross Sea and Prydz Bay continental shelves, the Weddell Sea slope, and the Wilkes-Adélie Land rise, thus providing evidence for a dynamic AIS (e.g., Hayes et al., 1975; Barker et al., 1988; Barron et al., 1989; O'Brien et al., 2001; Escutia et al., 2011; Galleoti et al., 2016; Levy et al., 2019). For example, sediment cores from the western Ross Sea provide direct evidence for orbitally controlled glacial-interglacial cycles between 34 Ma and 31 Ma (Galleoti et al., 2016). These sediments also show the ice sheet to be mostly terrestrial, with ice sheet calving at the coastline not taking place until ~32.8 Ma (Galleoti et al., 2016). Sediments recovered from the Wilkes-Adélie Land continental shelf also indicate an ice sheet reaching the coastline during the early Oligocene ~33.6 Ma (Escutia et al., 2011). However, sea-ice-related dinocyst species (e.g., *Selenopemphix Antarctica*) in sediments from the continental rise are only present during the first 1.5 million years of the early Oligocene and after the Miocene Climatic Optimum (17–14.8 Ma; Bijl et al., 2018). For the remainder of the Oligocene and Miocene, dinocyst assemblages in the Wilkes-Adélie Land margin resemble the present-day open-ocean, high-nutrient settings north of the sea ice edge, suggesting a more restricted seasonal sea ice environment (Bijl et al., 2018). These findings suggest that the ice sheets dominantly retreated to their terrestrial margins, which is in agreement with late Oligocene sedimentologic, geochemical, and biogeochemical data obtained from coeval sediments pointing to terrestrial ice sheets and warm oligotrophic waters (Hartmann et al., 2018; Salabarnada et al., 2018).

The first major expansion of terrestrial ice sheets across the Ross Sea continental shelf, based on ice-proximal marine sediments recovered by DSDP Leg 28, took place at 24.5–24 Ma (Levy et al., 2019). This expansion coincides with disconformities reported in the coastal CRP record (Naish et al., 2001). These records provide direct evidence for a major episode of global cooling and ice sheet expansion previously indirectly inferred from oxygen isotope data (known as the Mi-1 event; e.g., Zachos et al., 2001a,b; Hauptvogel et al., 2017; Figure 5). This significant transition from dominantly terrestrial to marine ice sheets corresponds with a drop in the levels of CO_2 below 600 ppm, which remained below this value for most of the Neogene (Levy et al., 2019). These results provide insight into the potential for a threshold behavior of the AIS at CO_2 concentrations of 600 ppm (e.g., Galleoti et al, 2016; Levy et al., 2019).

A period of global warmth reversed the previous ice growth on Antarctica with global temperatures and atmospheric CO_2 concentrations similar to those projected for the coming centuries. This time interval includes the Miocene Climatic Optimum (MCO; 17–14.8 Ma; Figure 5), a period of global warmth during which average surface temperatures were 3°–4°C higher than today. Drill cores collected from the ice-proximal ANDRILL site in the Ross Sea indicate open water to ice-proximal conditions during the MCO (Levy et al., 2016). Recent drilling on the Ross Sea continental shelf during IODP Expedition 374 also reveals the presence of shallow open water conditions during the MCO (McKay et al., 2018). In the Wilkes-Adélie Land, both dinocyst assemblages and paleotemperature data in sediments from IODP Expedition 318 indicate warm ocean conditions during the MCO, suggesting this marine-based sector of the East Antarctic Ice Sheet to be highly sensitive to ocean warming (Sangiorgi et al., 2018).

A combination of sedimentary evidence from an ANDRILL drill core in the Ross Sea (Levy et al., 2016) and numerical ice sheet modeling (Gasson et al., 2016) demonstrated the potential for tens of meters of early-mid Miocene sea level variability driven by AIS fluctuations. These studies substantially modified the conclusions of previous modeling, which showed a strong insensitivity of the continental AIS once it formed (Huybrechts, 1993; Pollard and DeConto, 2005).

The early Pliocene (~5–3 Ma) has received much attention because it is characterized by global temperatures comparable to those predicted for this century (IPCC, 2013) and atmospheric CO_2 concentrations similar to today (400 ppmv; Pagani et al., 2010; Figure 5). Foster and Rohling (2013) inferred atmospheric CO_2 values of 400 ppmv to represent a major threshold in the sensitivity of global ice sheets to climate change. They suggest that significant sea level rise (~9 m) is likely to occur at equilibrium under atmospheric CO_2 levels of 400–450 ppmv, implying significant melting in Antarctica. ODP Leg 119 drilling on the Prydz Bay continental shelf provided glimpses into the Neogene glacial history of East Antarctica and evidence for glacial fluctuations across the shelf during the late Miocene and the Pliocene (Barron et al., 1991; Passchier, 2011). On the western Antarctic Peninsula continental rise, ODP Leg 178 obtained a detailed record of glaciation, which suggested that the Antarctic Peninsula Ice Sheet was large enough to migrate regularly to the shelf edge over the past 10 million years (Barker et al., 1999), with extended periods of open water during the early Pliocene (e.g., Escutia et al., 2009). In Prydz Bay, elevated surface ocean temperatures of ~5°C were inferred in the early Pliocene (4.2–3.7 Ma) continental rise data obtained during ODP Leg 188 (Whitehead and Bohaty, 2003; Escutia et al., 2009). However, ice-proximal records from coeval intervals are still required from these two margin sectors to interpret the observed changes in terms of AIS grounding line dynamics and sea level.

Ice-proximal sediment cores recovered by ANDRILL from the Ross Sea contain intervals of diatomite that imply open water conditions and periodic retreat of the ice shelf over the drill site in Pliocene times (e.g., Naish et al., 2009; McKay et al., 2012a; Risselmann and Dunbar, 2013). As a result, there may have been a sea level rise greater the 6 m during Pliocene and early Pleistocene warm periods (Dutton et al., 2015), as supported by ice sheet modeling that simulates episodes of WAIS collapse (Pollard and DeConto, 2009). Sea level records based on paleo-shorelines and sequence stratigraphy on continental margins (e.g., Miller et al., 2013; Naish and Wilson, 2009) suggest Pliocene sea level could have been ~20 m higher than present, although the precise value remains highly uncertain (Rovere et al., 2014). This implies retreat of some sectors of the EAIS, thought to be more stable, in addition to melting of the Greenland and the West Antarctic Ice Sheets.

IODP Expedition 318 in the Wilkes-Adélie margin drilled one of the sectors where the EAIS is marine-based (Escutia et al., 2011, 2014; Figure 3). Iceberg debris accumulation in the sediment recovered from the continental rise provides a record of ice sheet growth and decay that is orbitally paced (Patterson et al., 2014). In addition, the geochemical provenance of detrital material recovered from this deepwater site provides evidence for repeated retreat of the marine-based EAIS inland into the Wilkes Subglacial Basin during the early warm Pliocene (5–3 Ma; Cook et al., 2013), supporting the notion of high Pliocene sea level. Importantly, some episodes of landward retreat of the ice sheet are also recorded in some coeval sediments recovered from the Wilkes-Adélie Land continental shelf, indicating repeated times with no sea ice and open marine conditions (Orejola et al., 2014; Reinardy et al., 2015).

The outcomes from drilling in Wilkes Land (Cook et al., 2013) and in the Ross Sea (Naish et al., 2009) forced a new generation of continental-scale ice sheet models that simulate glaciological (i.e., hydro-fracturing, marine ice sheet instability [MISI], and marine ice cliff instability [MICI]) and oceanographic processes, and better reconcile reconstructions of proximal ice sheet extent and far-field sea level from geological data (Gasson et al., 2016; Pollard et al., 2015; Golledge et al., 2017). The paleodata calibrated ice sheets models now reproduce 13–17 m of sea level rise from Antarctica, which better reconcile with reconstructions of proximal ice sheet extent and far-field sea level records of ~20 m (Miller et al., 2012; Dutton et al., 2015), providing revised global sea level predictions for IPCC scenarios. They also identify ~400–500 ppm CO_2 as a potential threshold for marine-based ice sheet stability (e.g., Gasson et al., 2016; Levy et al., 2016). Moreover, extremely low concentrations of cosmogenic ^{10}Be and ^{26}Al isotopes have been found in quartz sand extracted from a land-proximal marine sediment core from ANDRILL (Shakun et al., 2018). This record indicates that land-based sectors of the EAIS that drain into the Ross Sea have been stable throughout the past eight million years, meaning that 30 m is likely an upper bound for maximum Pliocene sea level, when combining the 22 m from the AIS plus 7 m from Greenland ice sheet melting (Shakun et al., 2018).

Pleistocene warmer-than-present interglacials are relevant to understanding ice sheet sensitivity to very small increases in global or hemispheric surface temperature. Reconstructions suggest global sea levels were 6–9 m higher during Marine Isotopic Stage (MIS) 5 (128–116 ka) and 6–13 m higher during MIS 11 (410 ka; e.g., Dutton et al., 2015).

Marine sedimentological and geochemical records from IODP Expedition 318 in the Wilkes-Adélie Land margin provide evidence for ice margin retreat in the vicinity of the Wilkes Subglacial Basin during MIS 5, MIS 9 (337 ka), and MIS 11 (Wilson et al., 2018). Retreat occurred when Antarctic air temperatures were at least 2°C warmer than pre-industrial temperatures for 2,500 years or more. This study points to a close link between extended Antarctic warmth and ice loss from the Wilkes Subglacial Basin, providing ice-proximal data to support a contribution to sea level from a reduced East Antarctic Ice Sheet during warm interglacial intervals. Sediments from the Ross Sea suggest that the WAIS collapsed during at least one Pleistocene interglacial (Scherer et al., 1998), but high-quality continuous (or at least more complete) Quaternary sediment records are still lacking, clouding the timing and magnitude of specific Pleistocene retreats (e.g., McKay et al., 2012b). All these records, however, point to sensitivity of the AIS under pre-industrial levels of CO_2. Proximal drill core records capturing "super-interglacials" of the past one million years are critically needed to validate models implying AIS collapse as recently as ~125,000 years ago.

Ultra-high resolution marine sedimentary records from the last deglaciation during the Holocene (comprising the last ~12,000 years) have been collected from Antarctica's margins by ODP Leg 178 at Site 1098 (Domack et al., 2001; Shevenell and Kennett, 2002; Leventer et al., 2002; Shevenell et al., 2011) and IODP Expedition 318 at Site U1357 (Escutia et al., 2011). These records have enabled comparisons between ice core and sediment records, which are fundamental to understanding the impacts of past climate changes on the ice-proximal marine environment. These records are key to understanding the evolution of climate teleconnections presently impacting Antarctica's ice sheets and sea ice (e.g., Yuan, 2004; Rignot et al., 2019), such as recently shown by geological observations of oceanic forcing of marine-based ice sheets (e.g. Hillenbrand et al., 2017; Etourneau et al., 2019).

Additional data are expected to come from the most recent IODP expedition to Antarctica, Expedition 374 (January–March 2018). This expedition aimed to evaluate the Neogene to Quaternary West Antarctic Ice Sheet variability and the associated oceanic forcings and feedbacks (McKay et al., 2018). Cores recovered span the early Miocene to the late Quaternary. Sediments recovered from continental shelf sites are expected to allow reconstruction of past glacial and open-marine conditions in the early and middle Miocene and of the first major continental shelf-wide expansion and coalescing of ice streams advancing from both East and West Antarctica, and also allow testing the hypothesis that ocean heat flux onto the continental shelf is important for ice sheet mass balance (McKay et al., 2018). Sediments recovered from the continental slope and rise are of Pliocene and Pleistocene age and will allow comparison with coeval shelf sediments in order to establish ice sheet dynamics-ocean linkages.

In addition, there are two scheduled IODP expeditions in 2019, Expedition 379 to the West Antarctica's Amundsen Sea, and Expedition 382 to the Weddell Sea (Figure 4). Amundsen Sea drilling on the continental slope and rise is aimed at a broad time window, from the Paleogene to present, but with a key objective of constraining the recent behavior and sensitivity of the WAIS and connections between ice sheet retreat and ocean temperature. Complementary drilling in the Weddell Sea, in the path of frequent icebergs traveling in the Weddell Gyre, will target a record of ice-rafted debris and its provenance as far back as the Miocene. Together, these drilling expeditions will provide an improved picture of WAIS variability on a range of timescales relevant to both geological and societal perspectives.

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LOOKING TO THE FUTURE

Knowledge gained from drilling marine sediments in and around Antarctica and the Southern Ocean is providing valuable insights into some of society's most pressing environmental concerns, including ice sheet stability and global sea level rise. However, this knowledge currently relies on data from only a few locations around the large Antarctic continent (Figure 1). Nevertheless, what has emerged over the last 50 years of scientific ocean drilling and from modern observations is that different Antarctic glacial catchments respond differently to climate perturbations (e.g., Golledge et al., 2012, 2017). The sparsity of paleoenvironmental records obtained to date hampers full understanding of temporal and spatial patterns and drivers of Antarctic ice volume change. These records provide only the basic framework for understanding past Antarctic Ice Sheet behavior.

The Antarctic and Southern Ocean Science Horizon Scan carried out under the auspices of the Scientific Committee on Antarctic Research identified several high-priority scientific questions that need to be addressed in the next 20 years and beyond (Kennicutt et al., 2014). The Horizon Scan was followed by the Council of Managers of National Antarctic Programs (COMNAP) Antarctic Roadmap Challenges (ARC) project designed to examine the steps necessary to enable the community to conduct research that will answer these high-priority questions (Kennicutt et al., 2016). Both exercises consulted the international Antarctic research community to define a collective vision of one possible future path and the necessary requirements to fully realize the promise of Antarctic research. Two of the most pressing priorities of relevance to society and policy are understanding the response of Antarctica's ice sheets and the Southern Ocean to climate change, and improving estimates of the ice sheets' contributions to global sea level rise. These topics have also been listed as priorities in the National Academies of Sciences, Engineering, and Medicine (2015) report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research*. Furthermore, the IPCC's Fifth Assessment Report (2014) identified the future evolution of the Antarctic Ice Sheet, particularly of its portions grounded on land that are below sea level (marine-based), as one of the most dramatic unknowns in global climate predictions, hampering reliable estimations of future sea level rise.

Improved predictions of ice sheet variability and its responses to climate change drivers are essential, because both polar regions are the fastest warming areas on Earth (e.g., Church et al. 2003). The integration of a broad spatial range of geological data into coupled models (e.g., ice sheet-glacial isostatic adjustment-ocean-atmosphere) will be critical for describing and predicting realistic ice sheet dynamics and thus improving projections of future sea level rise. To gain a better understanding of the mechanisms and processes responsible for observed changes in Antarctica's ice sheets and the Southern Ocean (i.e., the influence of bed topography and glacial substrates, ice sheet and sea ice extent variation, oceanic and continental temperatures, meltwater, and other basic parameters) requires obtaining samples from key locations, which will improve knowledge of boundary conditions for numerical models (e.g., Colleoni et al., 2018). There needs to be an emphasis on obtaining, when possible, high resolution records (i.e., orbital to annual) of cryosphere-ocean-atmosphere interactions leading up to and during past deglaciation episodes. These records are key to understanding how past changes in atmospheric circulation influenced the transport of ocean heat to the ice sheet grounding lines (Hillenbrand et al., 2017; Etourneau et al., 2019). They also are important for helping to define the nonlinear or variable ice margin retreat during climate warming, rather than having to assume a simple switch in the ice sheet models between advanced and retreated states. This will allow evaluation of the rates and magnitudes of sea level rise in future warming scenarios, a policy-relevant open question. These records are also critical for reconstructing equator-to-pole temperature gradients through time to better understand polar amplification and interhemispheric teleconnections (e.g., tropical-Antarctic teleconnections such as the El Niño-Southern Oscillation, Southern Annular Mode, and bipolar ocean see-saw).

Because different regions of the Antarctic ice sheet undoubtedly will reveal different glacial histories, the spatial and temporal coverage of Antarctic drilling is presently too limited to establish the temporal and spatial ice volume changes resulting from past complex ice sheet-ocean-atmosphere interactions. As mentioned above, the sedimentary sections recovered to date represent either coastal or offshore conditions, but rarely both in close proximity, and many sectors are still unsampled (Figure 1). To reconstruct the sensitivity of East, West, and Antarctic Peninsula Ice Sheets within a broad range of climatic (i.e., varying CO_2 atmospheric concentrations and temperatures) and oceanic (i.e., oceanic forcing of marine-based ice sheets) conditions requires drilling in different sectors of the Antarctic margin and in different paleoenvironmental settings (i.e., subglacial, ice, coast, continental shelf, continental rise, abyssal plain settings; see Figure 2). Scientific drilling in the Southern Ocean, from the coastline to the deep sea, using multiple platforms, to collect the geological records of climate and ice sheet history is needed to study ice-ocean interactions and the tectonic evolution of Antarctica/Gondwana and its influence on Earth's climate system. Scientific ocean and continental drilling are essential for obtaining these paleoclimate records, targeting, in particular, land (subglacial drilling)-to-coastal-to-deep-sea transects through amphibious drilling projects. Sectors of interest are those that will reveal ice mass loss and enhanced glacier flow increases closest to the sources of subsurface warmer modified circumpolar deep water (e.g., Rintoul et al., 2016; Figure 6). These sectors are likely to dominate sea level rise around Antarctica in the (near) future as more Circumpolar Deep Water is pushed against the glaciers by enhanced polar westerlies (Rignot et al., 2019).

For planning future Antarctic drilling projects for ice sheet reconstructions, the collection of new geophysical data around the margin through national and international partnerships is also critical. There are little or no existing data for many areas of the Antarctic margin, but these data are needed to assess the potential relevance of specific regions and sedimentary sections to understanding Antarctic Ice Sheet dynamics and related sea level changes. Such data are also

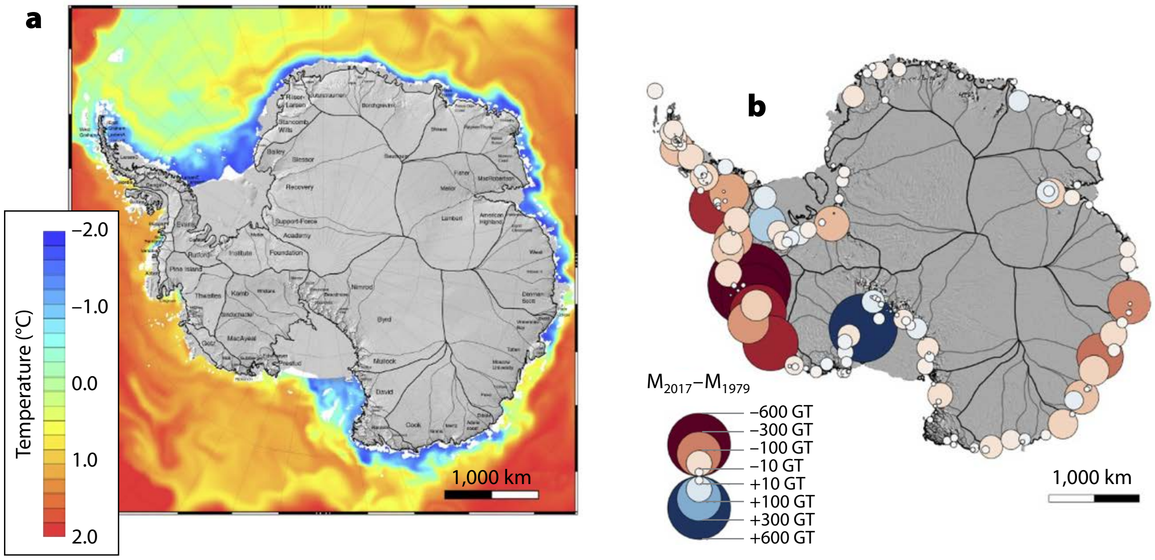

FIGURE 6. (a) Ocean temperatures at 310 m depth from the Southern Ocean State Estimate (SOSE) color-coded in °C from cold (blue) to warm (red). The white colors correspond to areas that are shallower than 310 m depth. (b) Total change in ice mass of major basins for 1979–2017. Blue colors = mass gain, red = loss. Circle radii are proportional to the absolute mass balance. *Modified from Rignot et al. (2019*)

needed for the development of paleotopographic and paleobathymetric reconstructions for key intervals that are critical for modeling ice sheet extension and retreat and the related surrounding ocean circulation. The availability of icebreakers is indispensable for providing access to research sites in year-round, ice-covered areas for high-resolution bathymetric mapping, geophysical data collection, and scientific ocean drilling.

As in the past, innovations in drilling technology, proxy development, and modeling will facilitate new scientific advances. For example, improvements that would allow the high-quality recovery of shelf glaciomarine sediments are needed. Continental shelf strata are the best archives for establishing the ages of grounding line advances and retreats of the Antarctic ice sheets, information that is key for understanding spatial and temporal changes in the continent's marine-based ice sheets and related sea level change. Recovery of these sediments to date by scientific ocean drilling has been challenging because of the physical characteristics of glacial tills and related marine deposits; the combination of soft sediments and gravel hinders successful sediment coring because these deposits "clog" the rotating drilling mechanisms. It is therefore essential for future scientific ocean drilling programs to continue to advance a technological agenda. In addition, new environmental data can be obtained by mining of legacy cores with innovative proxies. However, there are limitations to the use of legacy samples because they do not always contain the continuous and/or high-resolution sections that are necessary to progress in paleoclimate/paleoceanography/global sea level reconstructions. It is essential that scientific drilling programs have the technology in hand to lead these societally relevant research programs.

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ACKNOWLEDGMENTS

The authors are thankful for the opportunity to undertake this Antarctic scientific ocean drilling 50-year review and outlook into the future. We are especially thankful to two formal reviewers and to Anthony Koppers and Debbie Thomas for their useful comments on various aspects of the manuscript. Support for C. Escutia to conduct this activity comes from Grant CTM2017-89711-C2-1-P, CGL2016-75679P, co-funded by the European Union through FEDER funds.

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ARTICLE CITATION

Escutia, C., R.M. DeConto, R. Dunbar, L. De Santis, A. Shevenell, and T. Naish. 2019. Keeping an eye on Antarctic Ice Sheet stability. *Oceanography* 32(1):32–46, https://doi.org/10.5670/oceanog.2019.117.