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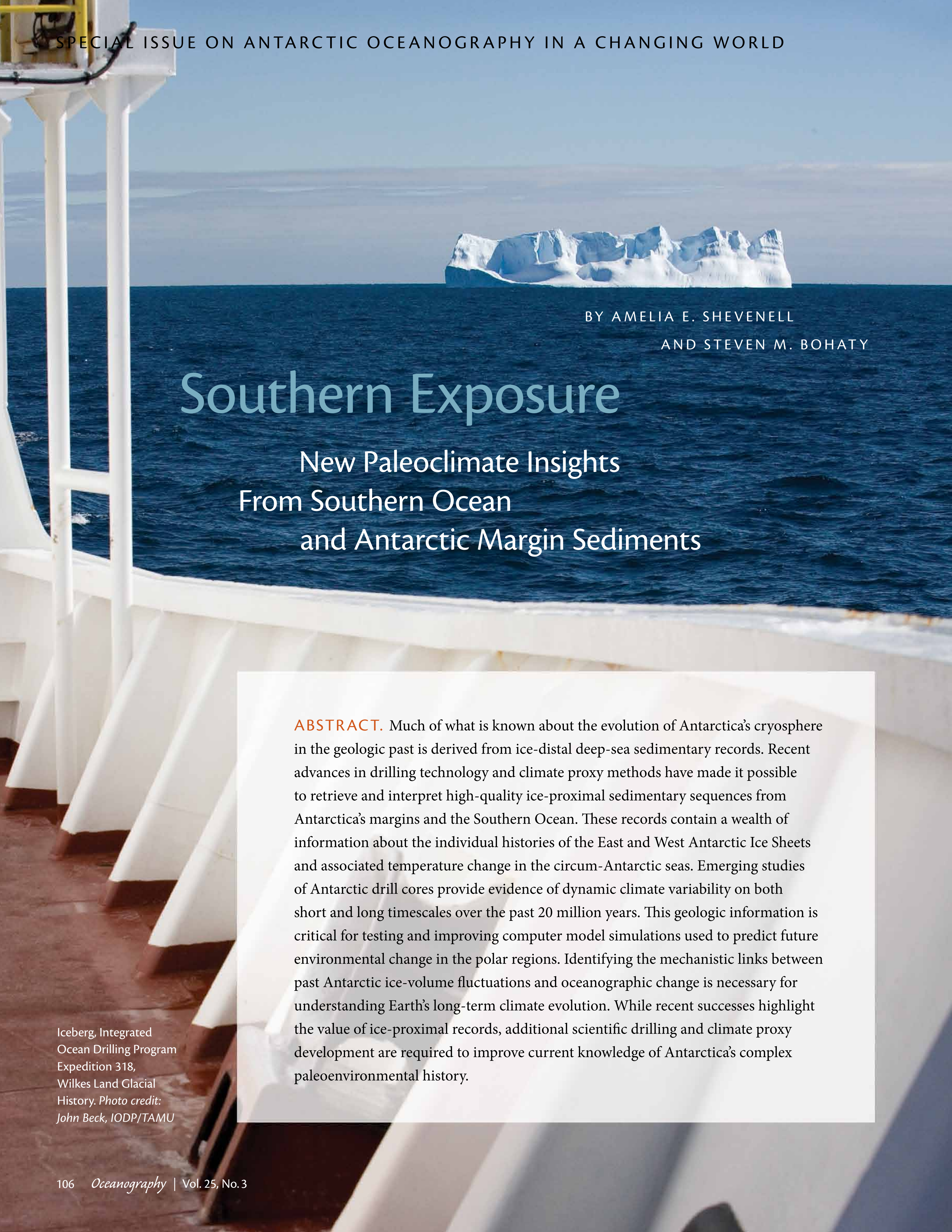

BY AMELIA E. SHEVENELL AND STEVEN M. BOHATY

Southern Exposure

New Paleoclimate Insights From Southern Ocean and Antarctic Margin Sediments

ABSTRACT. Much of what is known about the evolution of Antarctica's cryosphere in the geologic past is derived from ice-distal deep-sea sedimentary records. Recent advances in drilling technology and climate proxy methods have made it possible to retrieve and interpret high-quality ice-proximal sedimentary sequences from Antarctica's margins and the Southern Ocean. These records contain a wealth of information about the individual histories of the East and West Antarctic Ice Sheets and associated temperature change in the circum-Antarctic seas. Emerging studies of Antarctic drill cores provide evidence of dynamic climate variability on both short and long timescales over the past 20 million years. This geologic information is critical for testing and improving computer model simulations used to predict future environmental change in the polar regions. Identifying the mechanistic links between past Antarctic ice-volume fluctuations and oceanographic change is necessary for understanding Earth's long-term climate evolution. While recent successes highlight the value of ice-proximal records, additional scientific drilling and climate proxy development are required to improve current knowledge of Antarctica's complex paleoenvironmental history.

Iceberg, Integrated Ocean Drilling Program Expedition 318, Wilkes Land Glacial History. *Photo credit: John Beck, IODP/TAMU*

INTRODUCTION

The Southern Ocean and Antarctic ice sheets are critical components of Earth's climate system. Processes occurring in the Southern Ocean influence global ocean circulation, deepwater ventilation, heat transport, and carbon cycling, while the Antarctic cryosphere regulates global sea level and temperatures. Strong zonal atmospheric and oceanic circulation effectively limits tropical heat transfer to the high latitudes, resulting in cold air and sea surface temperatures (SSTs) in the Antarctic region. Over the last half-century, observations from Antarctica and the Southern Ocean indicate significant atmospheric and oceanic warming (Gille, 2002; Turner et al., 2005; Steig et al., 2009) associated with changes in circulation (Purkey and Johnson, 2010), sea ice extent (Stammerjohn et al., 2008), ice sheet stability (Rignot and Jacobs, 2002; Shepherd et al., 2004), and regional ecology (Vaughan et al., 2003). Climate models indicate that the polar regions are highly sensitive to rising atmospheric CO_2 concentrations and associated warming (Bitz et al., 2012), but the high-latitude response to ongoing and future warming in a high-CO_2 world remains uncertain due to a lack of understanding of complex interactions between the Antarctic cryosphere and the global climate system (IPCC, 2007). Specifically, we do not know if future oceanic and atmospheric warming in the southern high latitudes will result in significant instability and/or contraction of Antarctica's ice sheets. Informed estimates of Antarctic ice volume change are critical for predicting the timing and magnitude of future sea level rise due to glacial melting.

Since the 1960s, marine geologists have engaged in numerous scientific drilling campaigns that have sampled subseafloor geologic formations at coastal to abyssal depths in all ocean basins, and have obtained a diverse range of sedimentary records documenting Earth's climate evolution (Figure 1). Marine sediments from Antarctica's margins and the Southern Ocean contain detailed archives of past ice sheet behavior and regional physical and biological processes that have operated through time. Insights into these processes, obtained from the geologic record, can be used to assess the accuracy of global climate models and to better predict future climate change in response to increasing atmospheric CO_2 levels. Despite the climatic importance of the Antarctic region, only a handful of southern high-latitude drilling expeditions have been undertaken due to the logistical and technological challenges of traveling to and working in polar regions (Figure 1). Ship-based expeditions to the Antarctic margin often require long transit times and are inherently risky to due to harsh environmental conditions (e.g., permanent continental ice cover, sea ice and icebergs, low annual temperatures, and high winds) and limited rescue possibilities. Drilling on Antarctica's margins by the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and Integrated Ocean Drilling Program (IODP) has been further hampered by the technological challenges of achieving adequate core recovery in glacial marine sedimentary sequences.

Unraveling circum-Antarctic environmental and climatic signals in the geologic record has also proved challenging due to a general lack of calcium carbonate ($CaCO_3$) microfossils preserved in Antarctic margin sediments, which are required for traditional ocean temperature and ice volume reconstructions. Consequently, much of what we know about the evolution of Antarctica's ice sheets and the Southern Ocean through the Cenozoic Era (65 million years ago [Ma] to present) is derived from composite oxygen isotope ($\delta^{18}O$) records constructed using the $CaCO_3$ shells of benthic foraminifers preserved in lower-latitude deep-sea sedimentary sequences (Figure 2; Kennett, 1977; Miller et al., 1987; Zachos et al., 2001; Cramer et al., 2009). These records indicate progressive cooling and ice growth through the Cenozoic. Eustatic (global sea level) records from passive continental margins support $\delta^{18}O$-based ice volume interpretations acquired from distal deep-sea locations (Figure 2; Miller et al., 2005; Kominz et al., 2008). However, without direct records of past ice advance and retreat from Antarctica's margins, both the timing and magnitude of ice volume fluctuations and the relative contribution of Antarctica's ice sheets to global ice volume changes is uncertain. Thus, integrating discoveries from newly recovered ice-proximal records with distal deep-sea geochemical records (e.g., Naish et al., 2009; Cramer et al., 2011; McKay et al., 2012) is essential to improve understanding of climatic boundary conditions

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favorable for ice growth/decay and the individual histories of the East and West Antarctic Ice Sheets.

In the last half-century, various hypotheses have been proposed to explain the onset of continental-scale Antarctic glaciation at the Eocene-Oligocene transition (~ 34 Ma) and subsequent glacial-interglacial variations (e.g., Kennett, 1977; DeConto and Pollard, 2003). A leading hypothesis, supported by climate models and paleoclimate proxy data, is that Cenozoic Antarctic ice sheet development was driven by changes in atmospheric CO_2 (Figure 2; Pearson and Palmer, 2000; DeConto and Pollard, 2003; Pagani et al., 2005, 2011; DeConto et al., 2008; Pearson et al., 2009). If valid, this hypothesis has important implications for future Antarctic ice sheet stability and global sea levels with rising CO_2. Although data and models suggest an important role for atmospheric CO_2 in Cenozoic climate evolution, the timing and effects of other drivers of long-term climate change, such as the tectonic opening of circum-Antarctic gateways and the development of circumpolar circulation (e.g., Kennett, 1977), are not yet fully understood.

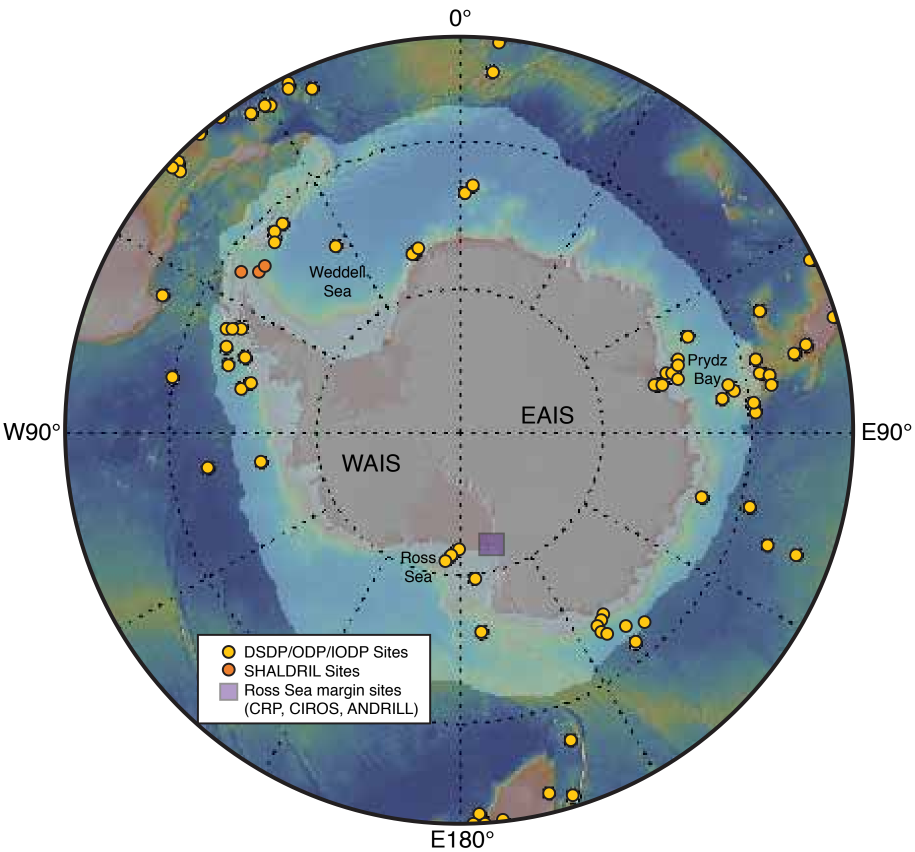


Figure 1. Bathymetric map of the Southern Ocean generated with GeoMapApp (http://www.geomapapp.org). Locations of Deep Sea Drilling Project/Ocean Drilling Program/Integrated Ocean Drilling Program (DSDP/ODP/IODP) sites (yellow circles), SHALDRIL2006 sites (orange circles; SHALDRIL = SHALlow DRILling), and Ross Sea margin sites (purple square; CRP = Cape Roberts Project; CIROS = Cenozoic Investigations of the Ross Sea; ANDRILL = ANtarctic Geological DRILLing). For reference, minimum summer sea ice extent (February 1977–2007, medium blue) and maximum winter sea ice extent (July 1977–2007, light blue) are overlain on the base map. EAIS = East Antarctic Ice Sheet. WAIS = West Antarctic Ice Sheet.

Recent technological and analytical developments have improved our ability to acquire and interpret sedimentary sequences from the Antarctic margin, providing new means to reconstruct Antarctica's past ice sheet dynamics. Newly developed ship- and ice-based drilling platforms and technologies, including those employed by IODP, the Cape Roberts Project (CRP), SHALlow DRILling (SHALDRIL), and the ANtarctic geologic DRILLing (ANDRILL) program, enable the recovery of nearly continuous (> 80% recovery) glacial marine sedimentary sequences from previously inaccessible (shallow and/or ice-covered) locations on Antarctica's margins (Barrett et al., 2007; Naish et al., 2008). In parallel, non-$CaCO_3$-based paleoceanographic and paleoclimatic proxies (e.g., Schouten et al., 2002; Belt et al., 2007) have been developed using organic biomarkers. When approached critically, the application of both existing and new climate proxies to Antarctic sediment core records allows researchers to: (1) gain insights into the Cenozoic evolution of Antarctica's ice sheets, (2) integrate high-latitude climate information from terrestrial, margin, and deep-sea records, and (3) undertake detailed data-model comparisons to understand the processes and feedbacks acting on the Antarctic cryosphere.

In this contribution, we highlight recent scientific advances in our understanding of Earth's climate system derived from high-quality marine sedimentary sequences recovered from the seabed around Antarctica's continental margin and in the Southern Ocean. We focus on three relatively warm geological time intervals during the past 20 million years: the last deglaciation/Holocene

(20–0 thousand years ago; Figure 3), the early to mid-Pliocene (5–3 Ma; Figure 4), and the middle Miocene (17–13 Ma; Figure 5). Central to the scientific advances in these time intervals is the availability of high-quality ice-proximal sedimentary sequences, application of robust sedimentological indicators of ice-sheet behavior and established geochemical proxies, and the development of new geochemical paleothermometers appropriate for use in $CaCO_3$-poor Antarctic margin and Southern Ocean sediments. Accurate ocean temperature reconstructions from Southern Ocean marine sedimentary sequences, in particular, are required to understand ice sheet history, global heat transport, climate sensitivity to greenhouse gas forcing, and polar amplification of global temperature trends. We emphasize that, while the following case studies represent recent success stories, further scientific drilling of Antarctica's margins and the Southern Ocean is required to develop a complete and unbiased view of Antarctica's role in Earth's climate system.

CASE STUDIES IN ANTARCTIC PALEOENVIRONMENTAL RECONSTRUCTIONS

Case Study 1: The Last Deglaciation/Holocene

Much of our knowledge of atmospheric chemical composition, circulation, and temperature change over the last 800,000 years comes from annually resolved ice core records obtained from Antarctica's ice sheets (e.g., Luthi et al., 2008). These records reveal a close coupling of atmospheric CO_2 and climate that is not fully understood, but likely regulated by physical and/or biogeochemical processes occurring in the ocean (e.g., Sigman et al., 2010).

Although a central role for the Southern Ocean in glacial-interglacial CO_2 variations has been hypothesized, evidence of direct Antarctic temperature-CO_2

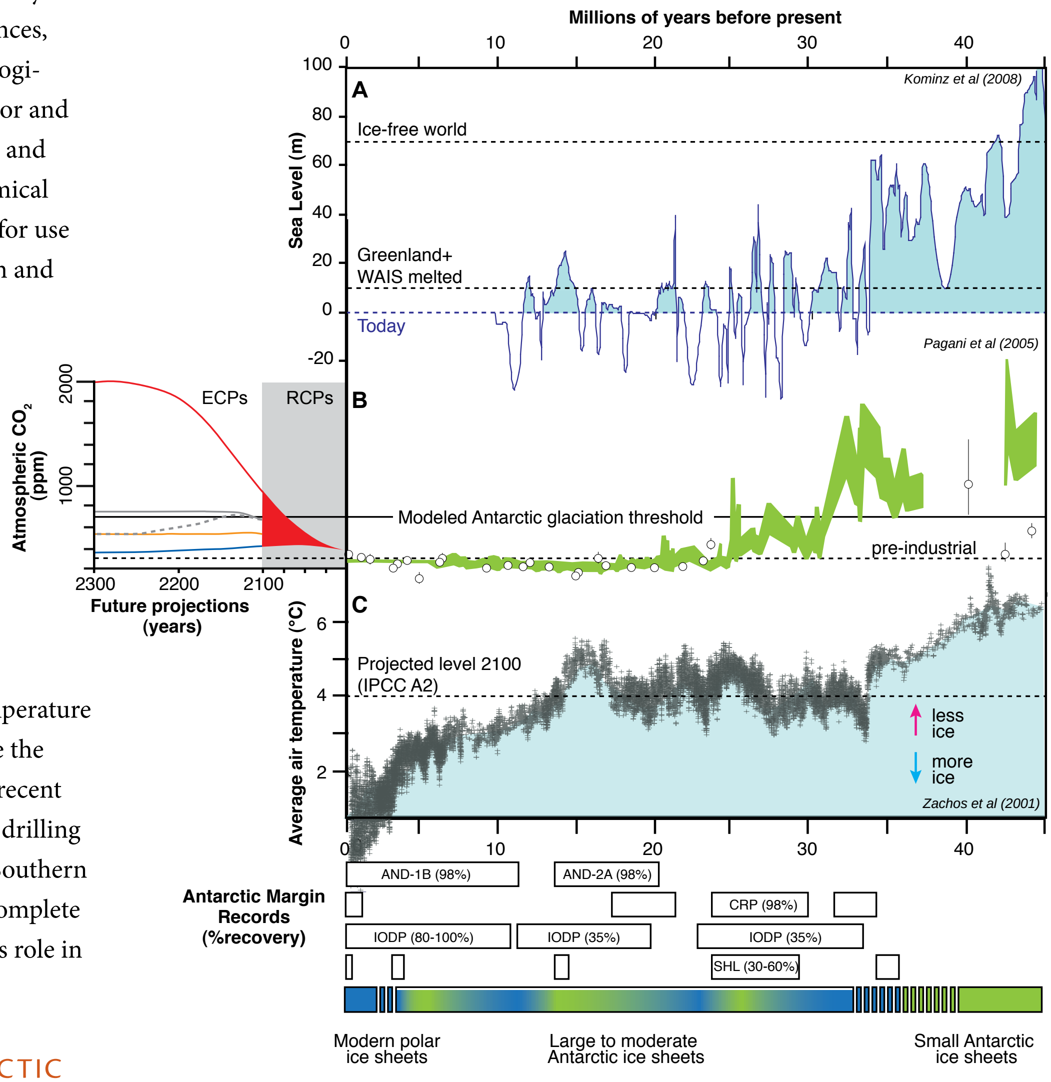


Figure 2. Earth's environmental evolution over the past 45 million years reconstructed from proxy data. (A) A sea level curve from the New Jersey margin (Kominz et al., 2008). WAIS = West Antarctic Ice Sheet. (B) Alkenone $\delta^{13}C$-based atmospheric CO_2 reconstructions (green; Pagani et al., 2005) and boron isotope pH reconstructions (open circles; Pearson and Palmer, 2000). The solid black line indicates model-derived CO_2 glaciation threshold for Antarctica (DeConto et al., 2008). The dashed line highlights pre-industrial CO_2 levels. The red envelope includes atmospheric CO_2 concentrations for the Representative Concentration Pathways (RCPs) to 2100 (IPCC, 2007; Meinshausen et al., 2011) and the red, gray, dashed gray, yellow, and blue lines indicate Extended Concentration Pathways (ECPs) to 2300 (Meinshausen et al., 2011). The ECPs are within the range reconstructed for the early Cenozoic, illustrating the importance of geologic drilling in providing long-term paleoclimatic context. (C) Global atmospheric temperature estimates based on the deep-sea benthic foraminifer oxygen isotope ($\delta^{18}O$) compilation of Zachos et al. (2001). The benthic foraminifer $\delta^{18}O$ signal reflects variations in both deep ocean temperature and global ice volume. White bars indicate key Antarctic margin reference sections recovered by the Cape Roberts Project (CRP), ANDRILL (AND), Integrated Ocean Drilling Program (IODP), and SHALDRIL (SHL); core recovery is indicated in parentheses. The green and blue-banded bars reveal the evolution of Antarctica's ice sheets, as inferred from geologic data.

coupling has only recently arisen via correlation of Antarctic ice core records and geochemical evidence from Southern Ocean marine sedimentary sequences (R.F. Anderson et al., 2009; Skinner et al., 2010; Burke and Robinson, 2012; Shakun et al., 2012). Geochemical records from sediments and deep-sea corals collected from the Atlantic and Pacific sectors of the Southern Ocean reveal increases in the flux of biogenic opal (a proxy for upwelling) and ventilation of nutrient-rich deep waters coincident with deglacial (20–10 thousand years ago) warming and rising atmospheric CO_2 (R.F. Anderson et al., 2009; Skinner et al., 2010; Burke and Robinson, 2012). These records indicate that changes in the Southern Hemisphere westerly wind field increased Southern Ocean overturning during the deglaciation, allowing relatively warm nutrient-rich intermediate to deep waters to return to the surface south of the Polar Frontal Zone (R.F. Anderson et al., 2009; Denton et al., 2010). Although the observed increases in biogenic opal flux to the sediments indicate that some nutrients were utilized regionally by phytoplankton, ice core CO_2 records (Monnin et al., 2001) suggest that phytoplankton production did not keep pace with upwelling, or that production was iron/micronutrient limited, resulting in a substantial release of old carbon to the atmosphere (Skinner et al., 2010).

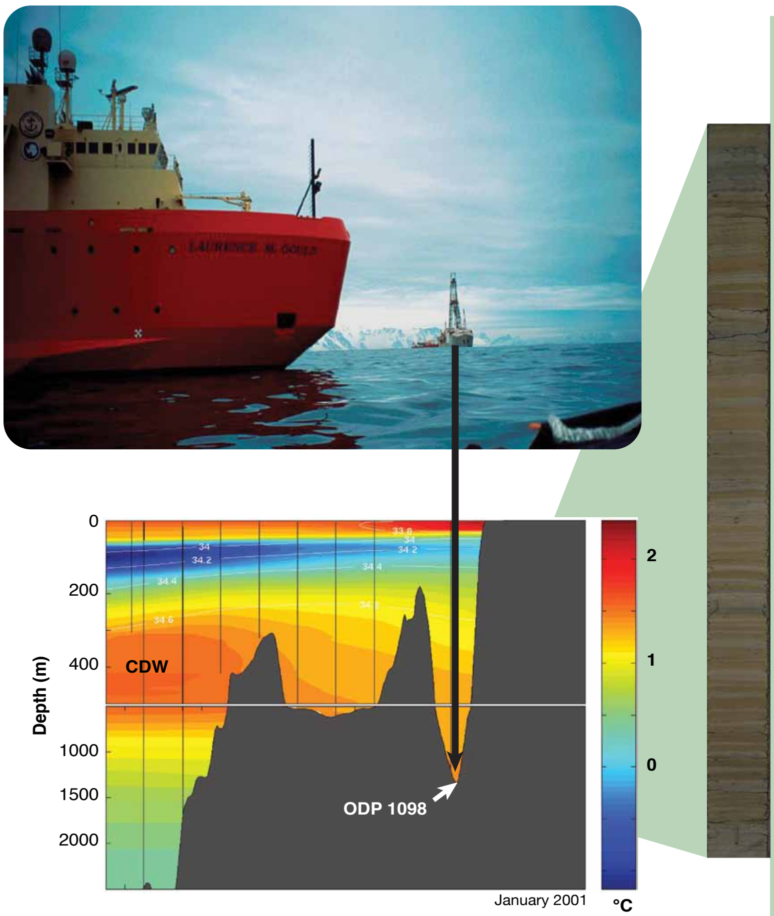
Although it is now clear that Southern Ocean processes play an important role in Late Quaternary glacial-interglacial climate change, the influence of newly upwelled warm nutrient-rich waters on the Antarctic cryosphere and the contribution of Antarctica's ice sheets to deglacial sea level rise remain speculative. Geophysical and sedimentologic reconstructions of Late Quaternary ice retreat have traditionally focused on identifying and dating the onset of ice-free conditions in different shelf regions around Antarctica's margins. (Ingólfsson et al., 1998; J.B. Anderson et al., 2002). In recent years, new geochemical proxies and improved dating techniques, integrated with ice sheet modeling, have shifted research focus toward identifying the forcings and feedbacks involved with Antarctica's most recent deglaciation (Leventer et al., 2006; Denton et al., 2010; Mackintosh et al., 2011). One new hypothesis for ice sheet retreat involves the sea level rise associated with Meltwater Pulse-1a (MWP-1a; Weaver et al., 2003). It has been proposed that MWP-1a destabilized Antarctica's floating ice margins, allowing newly upwelled warm Southern Ocean waters to increase basal melt rates and influence subsequent grounding line retreat (Mackintosh et al., 2011). While efforts are ongoing to determine the stability of the East Antarctic Ice Sheet during MWP-1a, we now know, based on modern observations (Rignot and Jacobs, 2002; Shepherd et al., 2004) and modeling (Pollard and DeConto, 2009) that ocean temperature estimates from the interface of Antarctica's cryosphere and the Southern Ocean are required to assess the relative importance of ocean heat on grounding line retreat and to validate existing ice sheet models.

Much of what is known about Antarctica's climate in the recent geologic past (15–0 thousand years ago) comes from ultra-high resolution (annual to centennial scale) marine sediments recovered from basins and drifts on the Antarctic continental margin (e.g., Domack et al., 2001; Leventer et al., 2006; Bentley et al., 2009; Escutia et al., 2011). Geochemical, sedimentological, and paleontological studies of these well-dated sequences reveal a wealth of high-quality information on past oceanographic fluctuations, sea ice conditions, meltwater influx, nutrient dynamics, and biologic productivity (e.g., Domack et al., 2001; Leventer et al., 2006; Bentley et al., 2009). Furthermore, these studies provide a geological perspective on modern regional climate change and the impacts of solar insolation, atmospheric circulation, oceanic heat, and sea level rise on Antarctica's ice sheets during deglaciation and through the Holocene.

Observations and computer models indicate that ice sheet stability is related to ocean temperatures at Antarctica's glaciated margins. Thus, reconstructing past Southern Ocean temperatures is a high-priority for paleoceanographers. An emerging organic geochemical paleothermometer, the tetraether index of 86 carbon atoms (TEX_{86}), based on the membrane lipid composition of marine archaea preserved in sediments (Schouten et al., 2002), holds promise for application in $CaCO_3$-poor Antarctic margin settings because marine archaea are abundant in Southern Ocean surface waters, their regional ecology is under investigation (Church et al., 2003), and their membrane lipids are present in Antarctic margin sediments (Kim et al., 2008; Shevenell et al., 2011).

A recent TEX_{86}-based core-top calibration and down-core study of Holocene ocean temperatures from the western Antarctic Peninsula demonstrates the regional potential of this paleothermometer (Figure 3; Shevenell et al., 2011). The TEX_{86}-based temperature record from ODP Site 1098 reveals early Holocene warmth followed by a 6,000-year cooling trend. This cooling highlights the importance of local (65°S) spring insolation on Southern Ocean temperatures and is echoed in Antarctic ice cores, model runs, and SST reconstructions from the Pacific sector of the Southern Ocean (Figure 3; Shevenell et al., 2011). On millennial timescales, the Site 1098 TEX_{86}-based temperature variability is consistent with local/regional terrestrial and marine temperature records, implying atmospheric forcing of western Antarctic Peninsula ocean temperatures during the Holocene (Shevenell et al., 2011).

Although the Site 1098 TEX_{86}-based temperature trends are generally consistent with independent local and regional paleoenvironmental records, further refinement of the absolute temperature estimates is required (Shevenell et al., 2011). In particular, the warm absolute TEX_{86}-derived temperatures, contrasting relative temperature trends interpreted from diatom paleocological studies (Sjunneskog and Taylor, 2002), and similarities between inferred temperature patterns, local (65°S) spring insolation, and spring-blooming diatom abundances (Sjunneskog and Taylor, 2002) at Site 1098 emphasize the need for additional studies of the TEX_{86}–temperature



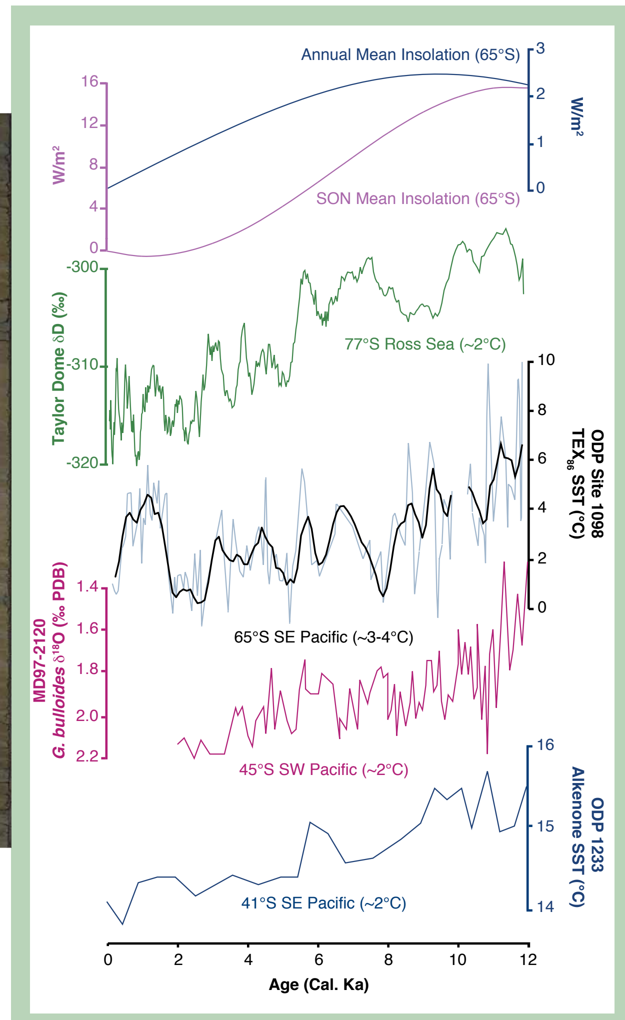


Figure 3. Detailed deglacial to Holocene climate records have been recovered from drilling expeditions to Antarctica's continental margins. One example of such a record comes from Ocean Drilling Program (ODP) Site 1098, drilled in Palmer Deep basin on the western Antarctic Peninsula margin (~ 1,000 m water depth) during ODP Leg 178. (a) During drilling, ODP's drilling vessel *JOIDES Resolution* had ice and logistical support from the R/V *Polar Duke* and the USAP's ARSV *Laurence M. Gould* (photo credit: A. Leventer). (b) The western Antarctic Peninsula is sensitive to the position of the Southern Hemisphere westerly wind field, which influences the storminess and presence of warm Circumpolar Deep Water (CDW) on the shelf, indicated in a typical austral summer cross section of ocean temperatures from Palmer Long Term Ecological Research (LTER) Line 6, which includes ODP Site 1098 (see Shevenell et al., 2011, for details). (c) The sedimentary sequence from Site 1098 is laminated, diatom-rich, and contains detailed deglacial to Holocene (13–0 thousand years ago) climate records (Domack et al., 2001). (d) TEX_{86}-derived temperatures (gray and black) from ODP Site 1098 indicate cooling since deglaciation (Shevenell et al., 2011). While the absolute temperature values will evolve as regional TEX_{86} calibrations improve, application of multiple existing calibrations to the Site 1098 data set indicate that the observed temperature trends are robust (Shevenell et al., 2011). TEX_{86}-derived temperatures are compared with local insolation (blue and purple), Antarctic ice core (green), and sub-Antarctic sea surface temperatures (SSTs; red and blue) from the Pacific Sector of the Southern Ocean, revealing similarities on orbital and millennial timescales (see Shevenell et al., 2011, for details).

relationship in the Southern Ocean and regional marine archaeal ecology (e.g., seasonality and depth of lipid production; Church et al., 2003; Shevenell et al., 2011; Kim et al., 2012). The application of TEX_{86} paleothermometry in Southern Ocean sediments is in its infancy. However, initial studies underscore its potential to improve understanding of the influence of oceanic heat on past and future stability of the Antarctic ice sheets.

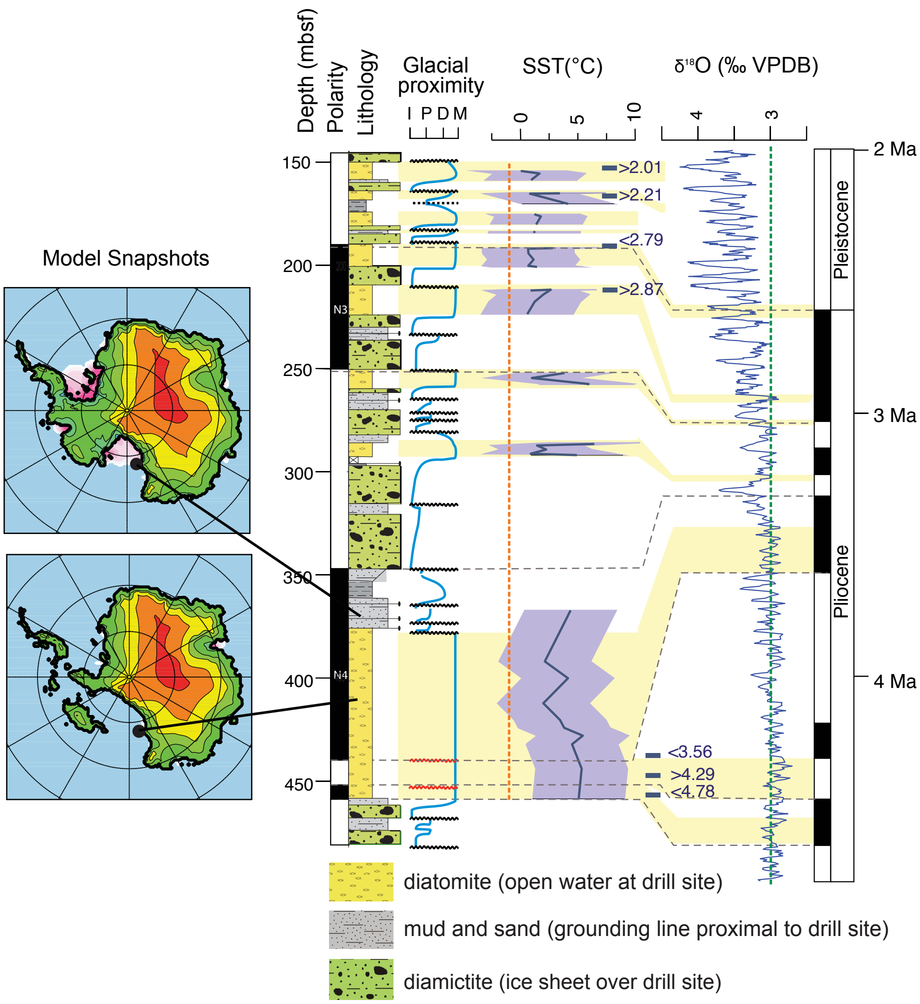


Figure 4. Summary of early Pliocene lithofacies and sea surface temperatures (SSTs) in the AND-1B (ANDRILL) drill core and model snapshots redrawn and modified from Naish et al. (2009), McKay et al. (2012), and Pollard and DeConto (2009). Lithofacies are plotted by depth, and sequences ages are constrained by integrated chronostratigraphy (Naish et al., 2009). Glacial proximity, a proxy for ice sheet extent, is based on lithofacies interpretation; proximity tracks the relative position of the grounding line (ice contact [I], ice-proximal [P], ice-distal (D), and marine [M]; Naish et al., 2009). TEX_{86}^{Low}-derived temperatures, with purple shaded error envelope and orange dashed line for present TEX_{86}^{Low}-derived Ross Sea temperatures, from interglacial deposits record a general cooling trend toward the onset of glacial conditions evident in the late Pliocene global benthic $\delta^{18}O$ stack (McKay et al., 2012; Lisiecki and Raymo, 2005). Observation and ice sheet model integration in the early Pliocene has enabled reconstruction of Antarctic ice sheet extent during a warm interval where atmospheric CO_2 concentrations were similar to present and provides insight to the forcings and feedbacks influencing the Antarctic cryosphere. Model snapshots of simulated ice volume during an interglacial and a glacial period in the early Pliocene are shown (Pollard and DeConto, 2009). Model results indicate that warm Circumpolar Deep Water (CDW) inundated the shelf during interglacial periods, suggesting a role for ocean heat in obliquity-paced fluctuations of the early Pliocene Antarctic cryosphere (Pollard and DeConto, 2009).

Case Study 2: The Early to Mid-Pliocene

Emerging Antarctic margin geologic data and model integrations underscore the importance of Southern Ocean temperatures on Antarctic cryosphere stability prior to the late Quaternary. Well-dated early to mid-Pliocene (~5–3 Ma) sediments recovered from Southern McMurdo Sound by ANDRILL (AND-1B) reveal orbitally paced (40,000 years) oscillations of the West Antarctic Ice Sheet (WAIS) grounding line at a time when Earth's average temperature was ~ 3°C warmer than present and atmospheric CO_2 levels were ~ 400 ppmv (Figure 4; Naish et al., 2009). Because Earth's present atmospheric CO_2 levels are similar to those of the early Pliocene (Figure 2; Pagani et al., 2010; Seki et al., 2010), this time interval is considered an analog for Earth's modern climate and may provide clues to future Antarctic cryosphere behavior (Pollard and DeConto, 2009; Pagani et al., 2010). The AND-1B record confirms the orbital pulse of Pliocene Antarctic ice sheets suggested by distal deep-sea $\delta^{18}O$ records (Figure 4; Lisiecki and Raymo, 2005; Raymo et al., 2006; Naish et al., 2009) and eustatic sea level reconstructions (Miller et al., 2012). Data from AND-1B, in conjunction with an ice sheet/ice shelf model, suggest that regional WAIS instability was driven by basal melting and grounding line retreat related to orbitally paced warm Circumpolar Deep Water (CDW) incursions (Figure 4; Naish et al., 2009; Pollard and DeConto, 2009). TEX_{86}-derived temperatures from AND-1B indicate the presence of relatively warm waters proximal to Antarctica in the early Pliocene that cool in late Pliocene as glacial conditions resume (Figure 4;

McKay et al., 2012). Sedimentological and diatom assemblage data also reveal warm regional ocean temperatures at the onset of many early Pliocene interglacials, providing independent support for TEX_{86}-derived temperatures (Naish et al., 2009; McKay et al., 2012).

In studies of Antarctic margin drill cores, an important challenge is to obtain ice-proximal evidence that addresses East Antarctica's contribution to early Pliocene eustasy (e.g., Raymo et al., 2011), with implications for the future stability of the East Antarctic Ice Sheet (EAIS). Sedimentologic and paleontological studies indicate surface-water warming (Whitehead and Bohaty, 2003; Escutia et al., 2009) and reduced spring/summer sea ice extent (Hillenbrand and Fütterer, 2002; Hillenbrand and Ehrmann, 2005; Whitehead et al., 2005; M. Williams et al., 2010) around Antarctica between 5 and 3 Ma. Provenance studies of ice-rafted detritus in Prydz Bay suggest periods of Pliocene EAIS instability (T. Williams et al., 2010), although overall ice-rafted debris accumulation rates were generally low (Passchier, 2011). Deciphering ice-rafting signals and developing additional proxy records from ice-proximal sites, including expanded early Pliocene sequences recovered by IODP from the Wilkes Land margin (Escutia et al., 2011; Tauxe et al., 2012), will be key to evaluating EAIS dynamics and Southern Ocean paleoceanography during warm intervals.

Case Study 3: The Middle Miocene

Like the early to mid-Pliocene interval, the middle Miocene climate transition (16.3–13.8 Ma) has long intrigued scientists (Savin et al., 1975; Kennett, 1977; Flower and Kennett, 1994; Shevenell et al., 2004). During the transition, deep-sea $\delta^{18}O$ records indicate major ice growth on Antarctica following the warmest interval of the Neogene, when globally distributed records indicate that the global carbon cycle was operating differently and atmospheric CO_2 may have been relatively low (Figure 2; Flower, 1999; Zachos et al., 2001; Pagani et al., 2005; Kurschner et al., 2008). Because a definitive link between ice growth and atmospheric CO_2 concentrations has yet to be established for the middle Miocene (Flower, 1999; Pagani et al., 1999), significant efforts are ongoing to determine the high-latitude climate response and to identify forcings and feedbacks involved in one of the most significant climate transitions of the Cenozoic.

Middle Miocene evidence emerging from the Indian and Pacific sectors of the Southern Ocean (Figure 5; Shevenell et al., 2004, 2008; Verducci et al., 2009; Majewski and Bohaty, 2010), the Ross Sea region (Naish et al., 2007; Warny et al., 2009; Harwood et al., 2008–2009; Feakins et al., 2012), the Antarctic Peninsula (J.B. Anderson et al., 2011), and the McMurdo Dry Valleys (Lewis et al., 2008) in the past decade provides an excellent example of the power of integrating terrestrial, shallow marine, and deep-sea records to develop a consistent picture of ice-proximal to distal high-latitude climate change. Southern Ocean SST and bottom water temperature records derived from the Mg/Ca of planktonic (Shevenell et al., 2004) and benthic (Shevenell et al., 2008) foraminifer $CaCO_3$ suggest the presence of warm waters around Antarctica during the Miocene Climatic Optimum (~ 17–14 Ma). ANDRILL recently recovered a thick middle Miocene sequence from the AND-2A drill core in southern McMurdo Sound that reveals a dynamic glacial environment and suggests retreat of the EAIS into the Transantarctic Mountains between ~ 17.1 and 15.5 Ma (Figure 5; Passchier, 2011; Sandroni and Talarico, 2011; Hauptvogel and Passchier, 2012). Independent marine, freshwater, and terrestrial palynological evidence from AND-2A also reveals peak regional atmospheric and oceanic warmth and meltwater input to the open Ross Sea at ~ 15.7–15.5 Ma, which may have been related to an increased presence of warm ocean waters on the continental margin and a southward shift in the Southern Hemisphere westerly wind field (Warny et al., 2009; Feakins et al., 2012). Terrestrial geomorphologic and paleontologic evidence from the McMurdo Dry Valley region also indicates warmer than present conditions during the middle Miocene Climatic Optimum (Lewis et al., 2008).

Existing ice-proximal and distal evidence reveals dynamic fluctuations of the East Antarctic Ice Sheet during the relatively warm climatic interval of the middle Miocene (Figure 5). Following maximum warmth of the Miocene Climatic Optimum, evidence from AND-2B suggests that the EAIS advanced (15.5 and 14.3 Ma) and coalesced with the WAIS after ~ 14.3 Ma (Sandroni and Talarico, 2011; Hauptvogel and Passchier, 2012). The 15.5 Ma date for the onset of EAIS advance is about one million years prior to the globally recognized deep-sea $\delta^{18}O$ increase (Figures 2 and 5; Zachos et al., 2001). However, this date is confirmed by $\delta^{18}O_{seawater}$ (a proxy for ice volume) data from the Southern Ocean, which indicates the orbitally paced onset of Antarctic ice expansion at 15.5 Ma, when Southern Ocean waters were relatively warm and atmospheric CO_2 was only slightly higher than present (Figure 5; Shevenell et al., 2008;

Lear et al., 2010). Although ice growth began at 15.5 Ma, about two million years prior to the node in Earth's orbital parameters identified at ~ 13.84 Ma (Holbourn et al., 2005), Southern Ocean surface cooling did not commence until 14.2 Ma, when SSTs cooled 6–7°C in a stepwise fashion, reaching a minimum at 13.8 Ma (Shevenell et al., 2004). Geomorphological evidence from the McMurdo Dry Valleys suggests a shift from wet-based to cold-based glaciation between 14.07 ± 0.05 and 13.85 ± 0.03 Ma, with an estimated mean surface temperature change of 8°C, similar to that observed in Southern Ocean SST records (Shevenell et al., 2004; Lewis et al., 2008). While these observations are consistent over a large geographic area and suggest a role for ocean heat, the dynamic middle Miocene behavior of the Antarctic cryosphere during an interval of relatively low atmospheric CO_2 presents a significant and ongoing challenge for ice sheet and climate modelers. Further research is also required to document trends and reduce pCO$_2$ uncertainty in the middle Miocene (Pagani et al., 1999; Pearson and Palmer, 2000; Kurschner et al., 2008).

RATIONALE FOR FUTURE ANTARCTIC DRILLING AND PALEOCLIMATE PROXY DEVELOPMENT

The scientific case studies presented here illustrate the recent technical and analytical progress by the international Antarctic marine geologic community toward recovering and interpreting high-quality ice-proximal Southern Ocean and Antarctic margin sedimentary sequences. These results provide important new insights into past ice sheet dynamics and marine temperature variations, particularly during pronounced warm intervals of the past 20 million years. It is now clear that the dynamic evolution of Antarctica's ice sheets can be reconstructed from ice-proximal geologic records and integrated with both

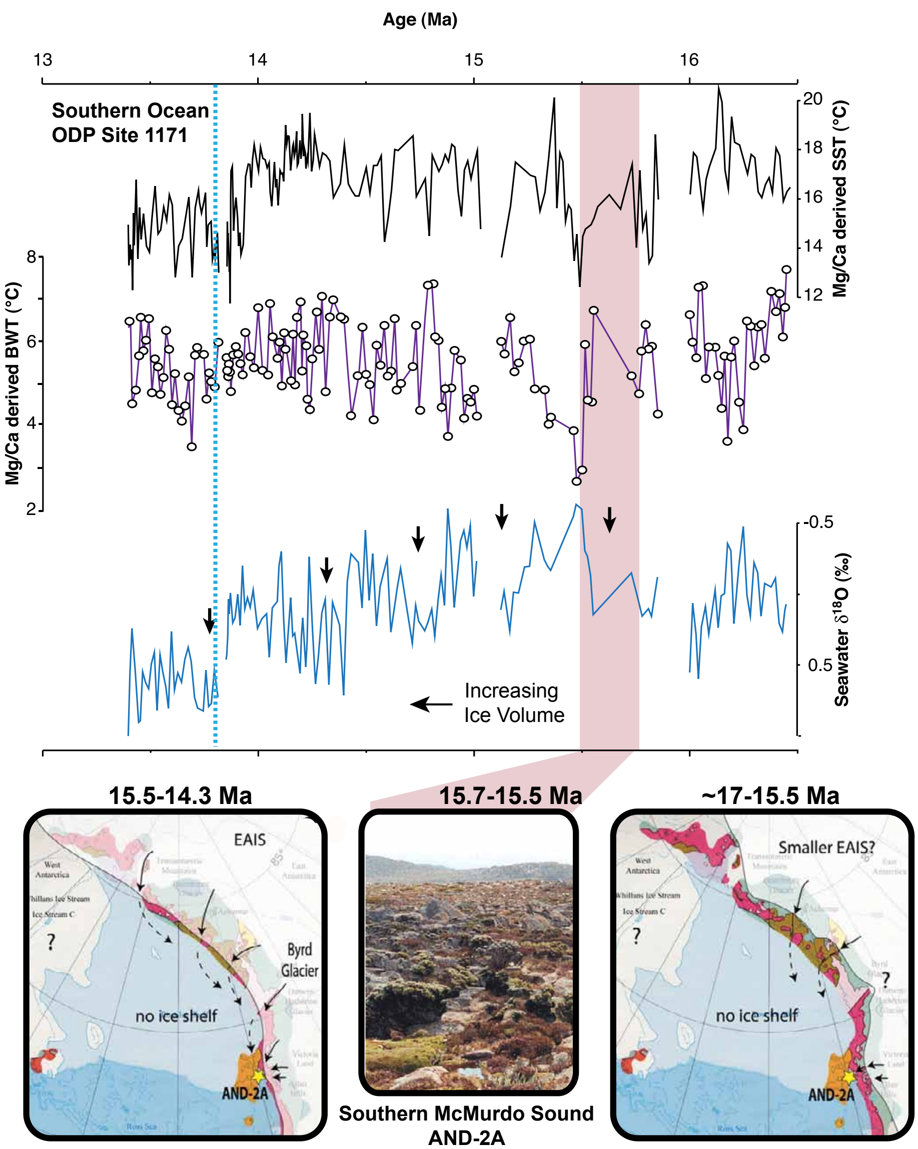


Figure 5. Integration of Southern Ocean sea surface (black), bottom water (purple with white circles), and ice volume (blue) data derived from foraminiferal stable isotope and trace metal proxies with data from ANDRILL Southern McMurdo Sound Site AND-2A. Ocean Drilling Program (ODP) Site 1171 paleotemperature data indicate generally warmer sea surface and bottom water temperatures during the Miocene Climatic Optimum (17–14 million years ago [Ma]; Shevenell et al., 2004, 2008). Heavy mineral provenance studies at AND-2A support a warmer climate between ~ 17 and 15.5 Ma and indicate that the East Antarctic Ice Sheet (EAIS) had retreated away from the coast and into the Transantarctic Mountains (Hauptvogel and Passchier, 2012). Pollen data from AND-2A provide evidence for tundra vegetation around the Ross Sea region between 15.7 and 15.5 Ma (pictured), suggesting this interval was a period of maximum regional warmth (indicated by the red bar; Warny et al., 2009). Heavy mineral provenance work from AND-2A indicates that at 15.5 Ma, the EAIS began to expand toward the coast until ~ 14.3 Ma (Hauptvogel and Passchier, 2012). Ice volume estimates from ODP Site 1171 indicate orbitally paced ice growth beginning at ~ 15.5 Ma during the warm Miocene Climatic Optimum (black arrows indicate glaciations) and continuing until the globally recognized deep-sea δ^{18}O increase at 13.8 Ma (blue dashed line; Shevenell et al., 2008).

deep-sea paleoceanographic records and climate/ice sheet models. By combining geological climate reconstructions with modeling efforts, it is possible to achieve a better understanding of the forcings and feedbacks involved in Earth's Cenozoic climate evolution and to constrain future environmental change. Because Antarctic margin sediments contain detailed histories of the East and West Antarctic Ice Sheets and information on the role of ocean heat in the evolution of Antarctica's ice sheets, there is a critical need for further scientific drilling on Antarctica's margins and in the Southern Ocean. It is now time to design coordinated multiphase drilling programs that use a multiplatform approach to drill inner-shelf to abyssal depth transects in climatically vulnerable regions (e.g., the Bellingshausen, Ross, and Weddell Seas, and Prydz Bay regions). Such efforts will require the cooperation of the geologic drilling, paleoceanographic, physical oceanographic, geophysical, and modeling communities.

A critical need also exists for coordinated regional proxy development and calibration studies. Many of the proxies currently used for the Antarctic and Southern Ocean environments were developed for use at lower latitudes. Due to extremes and complexities in Antarctic margin and Southern Ocean environments (e.g., low temperatures, seasonal insolation, sea ice, and meltwater), these proxies must be applied with caution in Antarctic margin sediments. For example, ongoing studies suggest the promise of applying organic geochemical proxies to Antarctic margin sediments (Shevenell et al., 2011; Kim et al., 2012), but further development and calibration of these proxies is critically required to improve the confidence of down-core interpretations. Collaborations among biological, chemical, and geological oceanographers should be undertaken in order to develop robust paleoclimate proxies for use in Antarctic and Southern Ocean sediments.

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