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Lessons from recent Antarctic drilling expeditions and future opportunities

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Recent expeditions recovered records of the climatically sensitive West Antarctica. East Antarctic drilling showed that the ice sheet was less stable than previously thought and prompted recalibration of ice-sheet models, emphasizing the need for future ice-catchment-scale land-to-sea drilling transects.

Why drill marine sediments around the Antarctic margin?

Multi-meter, global sea-level rise over the coming centuries to millennia will occur despite future mitigation and decline of atmospheric CO_2 concentrations. Excess heat taken up by the ocean will continue to drive ice-mass loss of the Greenland and Antarctic ice sheets (Fox-Kemper et al. 2021). The largest uncertainties in future sea-level-rise projections stem from processes that determine the rate and volume of ice-mass loss from Antarctica. Paleoclimate records, combined with modeling, can inform us about the state of Antarctica in the past, when greenhouse gas concentrations were similar to those anticipated over the next century.

Ice-sheet growth and decay over the last 40 Myr has heightened the vulnerability of the Antarctic Ice Sheet to ocean warming via bedrock erosion and sediment deposition. This vulnerability arises from deepening of subglacial basins where the ice sheet lies as deep as 2000 m below sea level (termed a marine-based ice sheet) on landward dipping beds, and from the growth of continental shelves across which deep-ocean heat exchange occurs (Colleoni et al. 2018). Marine-based glacier outlets are under threat from basal melting in both West Antarctica (e.g. Thwaites and Pine Island Glaciers) and glaciers in East Antarctica draining the Wilkes Subglacial Basin (e.g. Cook Glacier), and the Sabrina and Aurora Subglacial Basins (e.g. Totten, Vanderford, Denman Glaciers; Smith et al. 2020; Fig. 1a).

Sediment drilling on the continental shelf and slope, close to the Antarctic ice sheets, allows scientists to assess the processes and feedbacks governing ice-sheet change. Since the first marine-sediment drilling on the Antarctic margin by the *Glomar Challenger* in 1975 (Deep Sea Drilling Project –DSDP– Leg 28), which confirmed the age of the Antarctic Ice Sheet, there have been 12 deep-drilling expeditions to continental margins of Antarctica (Fig. 1a). International ocean drilling community-led organization resulted in four expeditions that were drilled between January 2018 and July 2019 (Fig. 2): Expeditions 379 to the Amundsen Sea, 374 to the Western Ross Sea, 382 to the Scotia Sea, and 383 to the South Pacific. Here we highlight the results from the Antarctic margin. We acknowledge the huge importance of records from Expeditions 382 and 383, which are further away from Antarctica, and show centennial–millennial-scale records of ice dynamics and Southern Ocean changes (Lamy et al. 2024) including records across the Mid-Pleistocene Transition (MPT) (Weber et al. 2022). The new IODP records for the MPT will be particularly valuable as international ice-coring campaigns recover new records of million-year-old ice.

Ocean drilling in West Antarctica

The Amundsen and Ross seas expeditions targeted unresolved questions related to the stability of West Antarctica during warmer-than-present climates of the Middle Miocene, Mid-Pliocene and "super interglacials" of the Pleistocene. These time periods are useful because they provide data on the ice-sheet, sea-ice and ocean state that are relevant for understanding Antarctica's future. Although the boundary conditions were slightly different (e.g. subglacial topography, duration and intensity of warming), ice-sheet modeling combined with proxy data help to refine an understanding of the different responses of Antarctica to climate warming (Mas e Braga et al. 2021).

Results from previous ocean drilling sites and sub-ice drilling (e.g. ANDRILL) provided critical snapshots of proximal ocean and environmental conditions during past warm climate intervals in the Ross Sea, but lacked continuous records of the associated ocean drivers that triggered ice retreat. The 2018–2019 International Ocean Discovery Program (IODP) expeditions aimed to drill on the continental shelf, slope and rise to understand the role of atmosphere–ocean–ice interactions in the Earth climate system. Some of the first results from Expedition 374 reveal that in the Early Miocene more elevated bedrock topography, and reduced interaction with the ocean, allowed for the existence of a much larger West Antarctic Ice Sheet (~15 m sea-level equivalent) compared to a smaller West Antarctic Ice Sheet today (5.3 m sea-level equivalent) (Marschalek et al. 2021).

The continuous Late Miocene to Holocene sediments from Expedition 379, combined with seismic profiles across the continental rise to shelf, revealed extensive West Antarctic Ice Sheet growth during the cold Pliocene periods, and long durations of

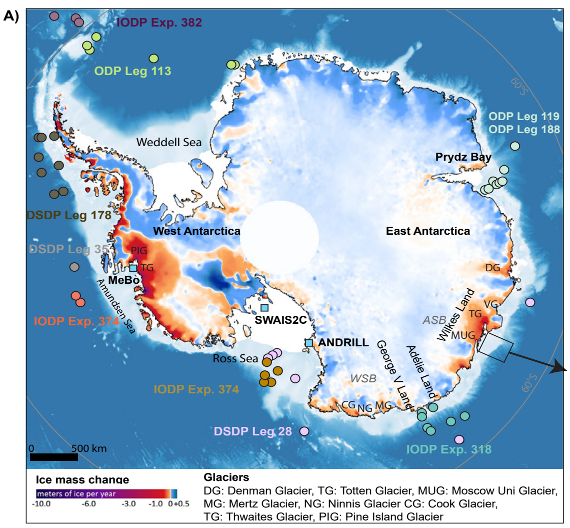
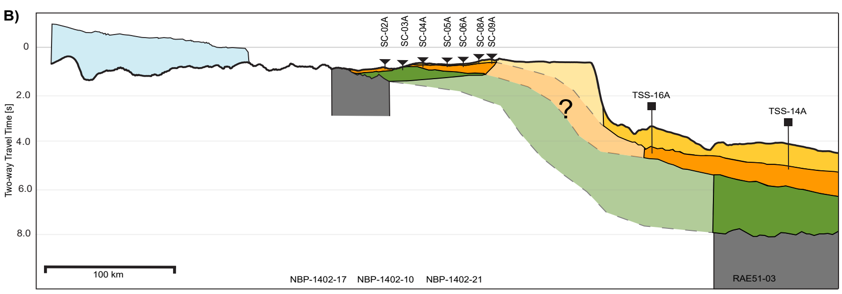


Figure 1: (A) Sediment drilling by DSDP/ODP/IODP on the Antarctic continental margin (circles) and other drilling on the shelf (squares). Ice-mass change (2003–2019) highlight sensitive sectors of marine-based ice (Smith et al. 2020). WSB: Wilkes Subglacial Basin. ASB: Aurora Subglacial Basin. **(B)** Cross-section of the seismic stratigraphy on the Sabrina continental margin (Donda et al. 2020) highlighting the cross-shelf data gap and proposed drill sites on the shelf (Pre-Proposal 931) and rise (Proposal 1002). Seismic data: Antarctic Seismic Data Library System (SDLS) (sdls.ogs.it/cache/index.jsp).



retreat during the warm Mid-Pliocene (Gohl et al. 2021). However, further drilling on the Amundsen Sea continental shelf is needed to establish the extent of ice-sheet collapse during past warm periods. Complementary Expedition PS-104 on the RV *Polarstern* collected the first Antarctic shelf cores drilled using the MeBo seafloor drill-rig in 2017. These sediment cores provided temporal snapshots of ice-proximal environments and deep-time development of West Antarctica, including the temperate rainforests of the Cretaceous, to the onset of Antarctic glaciation during the early Oligocene (Klages et al. 2024).

Ocean drilling in East Antarctica

Previous drilling campaigns targeting the vast East Antarctica Ice Sheet (ice-volume equivalent to 52.2 m of sea level) focused on Prydz Bay (DSDP 119 in 1988; Ocean Drilling Project –ODP– Leg 188 in 2000) and the Wilkes Subglacial Basin in Adélie and George V Land (Expedition 318 in 2010). We have much less data on the sensitivity of East Antarctica to climate change, but some ice catchments may be as sensitive to climate change as West Antarctica, for example the Wilkes and Sabrina-Aurora subglacial basins.

Expedition 318 advanced our understanding of East Antarctic variability over a range of timescales, and paleo calibrations of ice-sheet models in this region contributed to developments in models of future sea-level-rise projections (DeConto and Pollard 2016), and polar amplification in extreme greenhouse climates (Hollis et al. 2019). High-resolution, tree-ring-like Holocene records were drilled on the Adélie Shelf, which provided decadal-scale resolution of sea-ice change and associated climate drivers of sea-ice variability, over the last 2000 years (Crosta et al. 2021). Indications of retreat into the low-lying Wilkes Subglacial Basin during warm interglacial periods of the Pliocene (Cook et al. 2013), and super interglacials of the Pleistocene (Wilson et al. 2018) along with satellite-based observations, have sparked further multinational efforts to coordinate monitoring of the Cook Glacier system.

Future opportunities

To reduce uncertainties in the response of the Antarctic Ice Sheet to future climate scenarios, we need new site-survey data and drilling operations that target climatically sensitive ice catchments via land-to-sea (L2S) transects. There are only a handful of locations where site-survey seismic data connect the ice-proximal continental shelf to the deep-water continental rise. Coordinated international effort is required to fill these data gaps and minimize the long lead times associated with securing Antarctic logistics. Drilling beneath the grounding line (e.g. SWAIS-2C project) and shelf records (e.g. MeBo campaigns) provide direct, but stratigraphically discontinuous, records relative to the more continuous, sometimes high-temporal resolution continental-rise records. However, new cross-shelf seismic data and multiple drilling approaches are needed if we are to fully understand ice-sheet evolution during warmer than present climates. While insight into the thresholds and tipping points of West Antarctic are needed to inform current climate policies, far less is known about the much larger East Antarctic Ice Sheet, where small changes in the grounding line position can potentially have much larger sea-level impacts.

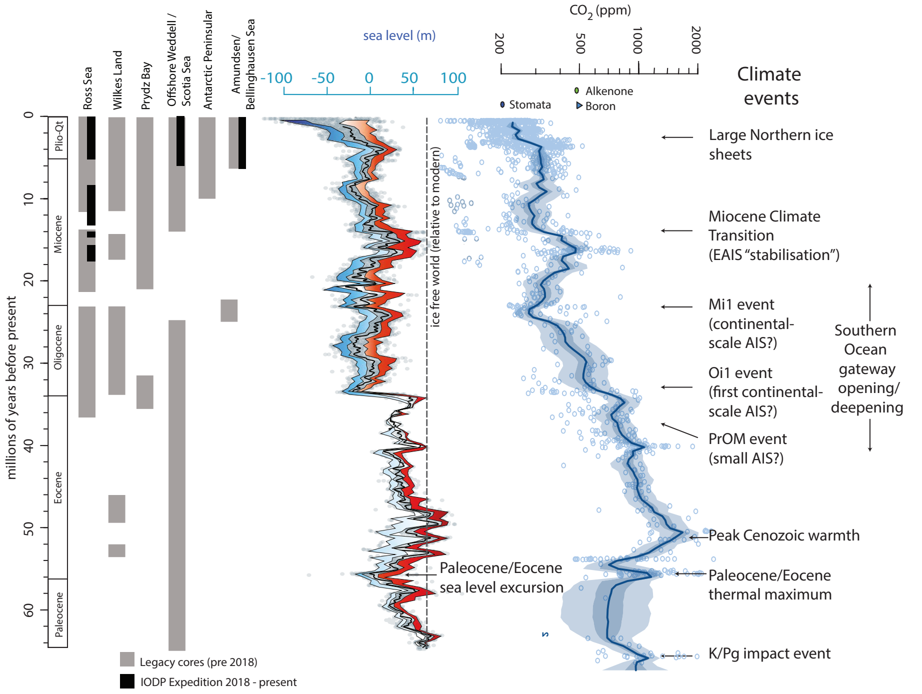


Figure 2: Climate and sea-level variability (CenCO_2PIP Consortium 2023 and references therein) with time intervals recovered by recent deep-ocean IODP Expeditions in 2018–2019 shown in black.

Below, we highlight promising future drilling targets:

West Antarctica

- The Amundsen Sea continental shelf to obtain a record of climate and ice-sheet evolution from the Cretaceous period to the present, focusing on the region of Antarctica currently experiencing the greatest change.
- A transect along the front of the Ross Ice Shelf to understand the climatic and tectonic controls on the early East to West Antarctic Ice Sheet histories during the Eocene and Oligocene epochs.
- Ultra-high resolution Holocene drift deposits in the fjords of the northern Ross Sea to provide baselines of oceanographic and biological changes in the world's largest marine protected area.

East Antarctica

- The margin of the Sabrina and Aurora subglacial basins in Wilkes Land to obtain ice-sheet and climate records from the late Miocene to Pleistocene on the continental rise, and the Cretaceous to Paleogene from the continental shelf (Fig. 1b).
- George V Land and Adélie Land shelf sediments to obtain greenhouse to icehouse paleoclimate and ice records of the marine-based Wilkes Subglacial Basin.
- A latitudinal transect across the Australian Antarctic Basin to explore the Cenozoic evolution of Antarctic Circumpolar Current and sea-surface temperature through time.

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