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East Antarctica's past foreshadows an uncertain future

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The glaciers of Greenland and Antarctica together contain enough water to raise global sea levels by more than 60 meters. With so much human infrastructure having been planned around current sea levels, if all the polar ice were to melt, the effect on human society would be devastating.

But Earth has seen warm climates and high seas before. During the Mesozoic era—the time of the dinosaurs, which ended 66 million years ago—the planet was far hotter than it is today. The polar regions were ice free.

Since then, temperatures and sea levels have generally been on the decline, and polar ice caps have grown to cover the Antarctic continent and Greenland. That overall trend was punctuated by dramatic bouts of warming and cooling, with glacial periods coming and going. More than a century of Antarctic exploration, on land and by sea, has built up a body of knowledge of how the ice sheet formed and how it has behaved. Geological records of past periods of ice instability during warm times are especially important for estimating the future consequences of anthropogenic climate change.

But there is still a lot more to discover. Global temperature and polar ice coverage aren't related by a simple one-to-one correspondence. Air and ocean temperatures don't always move in tandem, and a glacier can respond to changes in either or both. The collapse of a glacier is a mechanical process that, once initiated, takes time to play out. Glaciers don't all necessarily behave the same way, even in the same part of the world. The local details are important—and in a continent as vast as Antarctica, knowledge of them is incomplete. Much of the Antarctic coast has never been visited by a research vessel.

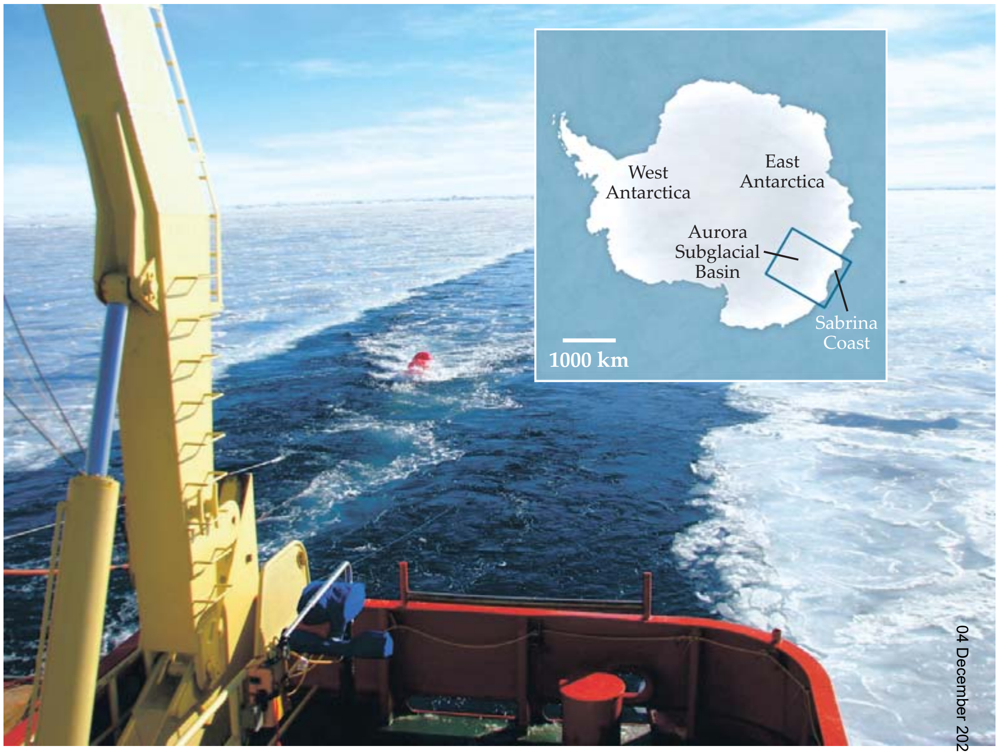

FIGURE 1. OFF THE COAST OF THE AURORA SUBGLACIAL BASIN in East Antarctica, researchers used seismic instruments deployed from the back of this icebreaker to acoustically probe the seafloor and the rock below it. (Photo by Sean Gulick; map courtesy of the University of Texas at Austin, Jackson School of Geosciences.)

Four years ago Sean Gulick (University of Texas at Austin), Amelia Shevenell (University of South Florida), and their colleagues undertook the first foray into one of those previously unexplored areas: the Sabrina Coast continental shelf off the shore of the Aurora Subglacial Basin (ASB) in East Antarctica, as shown in the map in figure 1. They've now analyzed the data they collected.[1]

From a combination of seismic measurements and sediment samples retrieved from the seafloor, the researchers found that the ASB glaciers had a dynamic past, advancing and retreating at least 11 times over a period of 30 million years. During much of that time, the atmospheric carbon dioxide concentration was close to what it is today, and the average global temperature was at a level it may reach again by the end of this century. And the ASB and other East Antarctic regions seem to have responded differently to past climate fluctuations.

Uncharted waters

Most attention to the future of Antarctic glaciers has focused on the precarious situation of West Antarctica. Because of the topography of the underlying rock, much of the West Antarctic ice is dangerously unstable, and some glaciers may have already entered a state of irreversible decline (see PHYSICS TODAY, July 2014, page 10).

The larger, thicker East Antarctic ice sheet rests on firmer foundations, but it's not immune to changes in climate. Evidence has been accumulating that parts of East Antarctica have been responsive to climate in the geological past, including under conditions not too far from what's expected in the coming decades.[2] But the studies are still few and scattered.

When they set out to add another data point to the map, in the austral summer of 2014, Gulick, Shevenell, and colleagues

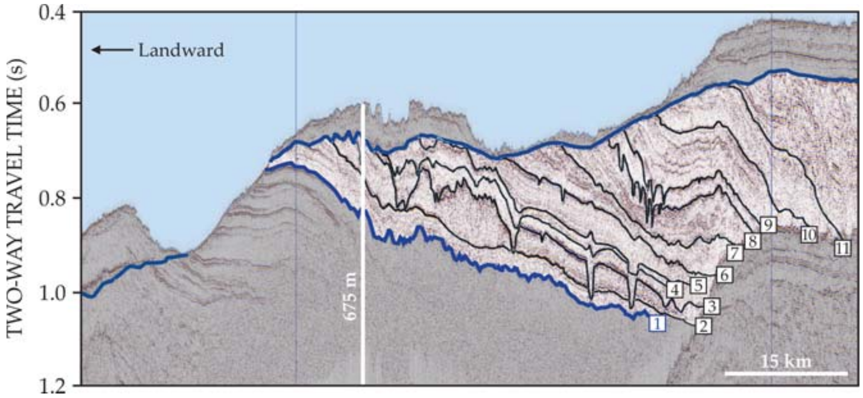

FIGURE 2. A SEISMIC PROFILE tells the history of glacial ice on the Sabrina Coast continental shelf, now underwater. The region between the two blue lines represents a period when the ice was responding dynamically to fluctuations in climate; each of the bold lines marked 1–11 is an erosion surface created by glacial advance and retreat. (Adapted from ref. 1.)

had their sights on Totten Glacier, on the western edge of the ASB. Aerial measurements had shown that Totten Glacier was losing mass faster than anywhere else in East Antarctica, and they wanted to know why. But polar field research doesn't always go according to plan. Sea ice and icebergs dictated where they could go and what they could do—sometimes on an hourly basis. Although conditions precluded reaching Totten Glacier, the researchers found a gap in the heaviest ice on the eastern portion of the Sabrina Coast. For four weeks they zigzagged over the continental shelf, gathering data and sediment samples.

A complicated past

As ice, meltwater, ocean currents, and accumulating debris shaped the continental shelf over tens of millions of years, they created layers of material with different acoustic properties. Seismic profiling—projecting sound waves toward the seafloor and recording their reflections—can uncover that structure, as shown by the profile in figure 2. The highlighted region corresponds to the period of glacial dynamicism: The layers below it formed before the arrival of ice to the continent, and the layers above formed after the East Antarctic ice sheet stabilized as a polar ice cap. The rough surfaces marked 1 through 11 were created by glacial erosion and correspond to periods of glacial advance and retreat. The layers between them are unusually thick. That means that when the glacier retreated, it must have pulled back far enough—hundreds of kilometers—to leave behind an open marine environment unsheltered by an overhanging ice shelf.

Some of the erosion surfaces are marked by narrow V-shaped gouges. Those so-called tunnel valleys are a common feature associated with glaciers in the Northern Hemisphere. But they're unusual for Antarctica, with only one known location in West Antarctica and no others in East Antarctica. They're attributed to surface meltwater that seeps through the porous glacial ice and gushes out the bottom. The formation of such deep tunnel valleys means that the ASB was exposed to warm air—as opposed to warm ocean water—for prolonged periods. Surface melting is thought to have little effect on Antarctic glaciers' behavior today. But it must have been a significant driver of glacial dynamics in the past—at least in the ASB.

Converting the seismic profile to a chronology is more complicated than counting layers like tree rings. Erosion surfaces form at irregular intervals, and there's no obvious connection between the features in the profile and events elsewhere on Earth. To pin down the timeline, the researchers collected sediment cores.

Because the ship wasn't equipped with a drill, the samples were collected with a piston corer, a long, heavy tube that plunges into the seafloor sediment like a straw into a milkshake. The cores, therefore, extended just a meter or two beneath the seafloor, so they had to be taken from just the right places where the strata of interest were naturally exposed. And the researchers had to choose those locations on the fly, without the benefit of a full analysis of their data. In fact, they didn't even get access to their sediments until almost six months later, back in their home labs.

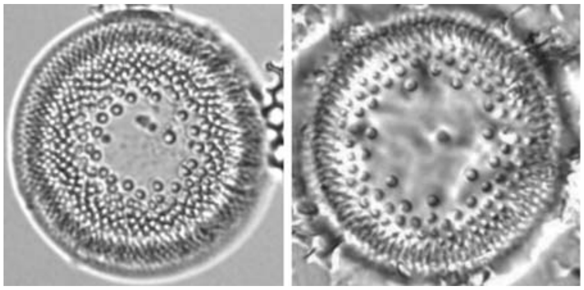

FIGURE 3. THESE FOSSIL DIATOMS, each 30 μm in diameter, were recovered from the sediments of the Sabrina Coast continental shelf. Their species—*Thalassiosira oliverana* (left) and *Actinocyclus ingens* (right)—flourished more than 4.8 million years ago. (Adapted from ref. 1.)

Happily, the researchers succeeded in obtaining sediment cores from key moments in the history of the Sabrina Coast, including one core that recorded the transition from the dynamic period to the polar ice-sheet regime. That crucial core was rich in the fossils of ancient silica-shelled diatoms, such as the ones in figure 3. Many of the microfossils were broken or degraded, but some were sufficiently intact to be identified by species. The diatoms in figure 3 are of different species, but they both roamed the seas at about the same time: between 8.6 million and 4.8 million years ago. Once the researchers had taken into account the species they didn't find in the core, the researchers concluded that the ASB glaciers probably settled down sometime between 6.9 million and 5.6 million years ago.

The result puts the ASB in an interesting contrast to other parts of East Antarctica. The nearby Wilkes Subglacial Basin, for example, seems to have still been advancing and retreating in response to climate fluctuations as late as 3.3 million years ago.[3] Still, it's hardly surprising that different parts of the East Antarctic ice sheet—a complex continent-scale system—don't all move in concert.

Estimates of atmospheric CO$_2$ levels from millions of years ago are subject to large uncertainties, but the past 25 million years have almost certainly included periods when the concentration exceeded the 400 ppm seen today. The global average temperature at the end of the ASB's dynamic period was likely 4 °C warmer than today, well within the span of projections for the year 2100 if drastic action is not taken to limit greenhouse emissions.

The broad similarities between past and future conditions are not predictive, but they are suggestive. Even the possibility of East Antarctic destabilization highlights the need for more data to better understand the ice sheet's vulnerability. Indeed, several more interdisciplinary expeditions will be visiting East Antarctica in the next few years, and Gulick, Shevenell, and colleagues have a pending proposal with the International Ocean Discovery Program to return to the Sabrina Coast with a scientific drilling rig. The longer cores that they can obtain with a drill could fill in the timeline and help the researchers understand exactly when and how the ice advanced and retreated in the past.

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2. See, for example, R. Levy et al., *Proc. Natl. Acad. Sci. USA* **113**, 3453 (2016); E. Gasson et al., *Proc. Natl. Acad. Sci. USA* **113**, 3459 (2016).
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Laser cooling delivers a Bose–Einstein condensate

The new, faster path to condensation could vastly speed up some quantum experiments.

It's been more than two decades since Carl Wieman, Eric Cornell, and their coworkers created the first Bose–Einstein condensate (BEC), confirming that a macroscopic population of integer-spin particles will pile into a single quantum ground state if cooled below some critical temperature. (See PHYSICS TODAY, August 1995, page 17.) After all those years, the recipe for creating the condensates remains virtually unchanged: Laser cooling chills the cloud of atoms as close to the critical temperature as it can, and when that technique can go no further, evaporative cooling does the rest.

Experimenters have long sought to bypass the evaporative cooling step, a slow process that jettisons most of a cloud's atoms in order to cool the remaining few. The process can take seconds, sometimes more than a minute, to unfold. Afterward, typically less than 1% of the original atoms remain.

Now MIT researchers led by Vladan Vuletić have used a laser technique known as Raman sideband cooling to take a cloud of rubidium atoms all the way to the condensation threshold—no evaporation needed.[1] From an initial gas of 2000 atoms, they can generate a BEC of more than 500 in just 300 ms—about the time it takes to blink an eye.

The Doppler limit

The threshold for Bose–Einstein condensation is often expressed in terms of a critical temperature. But a more fundamental quantity is the dimensionless phase-space density, the peak occupation per quantum state. Roughly speaking, that quantity describes the extent to which atoms' wavefunctions overlap. It grows as a cloud of atoms becomes colder and denser. As it surpasses a value of one, a BEC forms.

At the outset of their experiment, the MIT researchers' vapor of rubidium atoms has a phase-space density near 10^{-20}. To boost that value, the team captures the atoms in a magneto-optical trap and applies a standard laser cooling technique: Doppler cooling.