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West Antarctic Ice Sheet Change Since the Last Glacial Period

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The potential for rapid deglaciation, or collapse, of the 2-million-square-kilometer West Antarctic Ice Sheet (WAIS) in response to climate change is one of the most serious environmental threats facing mankind. The WAIS is a marine ice sheet with large parts of its ice grounded below sea level. Complete collapse would result in a global sea level rise of approximately 5 meters, with immense social, economic, and ecological consequences.

By R. D. Larter, K. Gohl, C.- D. Hillenbrand, G. Kuhn, T. J. Deen, R. Dietrich, G. Eagles, J. S. Johnson, R. A. Livermore, F. O. Nitsche, C. J. Pudsey, H.-W. Schenke, J. A. Smith, G. Udintsev, and G. Uenzelmann-Neben

While most experts consider such a collapse unlikely within the next few centuries, the Amundsen Sea sector has been identified as the most likely site for initiation of collapse, and it alone contains the potential to raise sea level by approximately 1.5 meters [*Vaughan*, 2007]. This would result in devastating flooding in many low-lying cities (e.g., New Orleans, London), agricultural areas (e.g., Netherlands, Bangladesh) and atolls (e.g., Maldives).

Glaciers flowing into the Amundsen Sea exhibit the most rapid recent decrease in surface elevation and grounding line retreat in Antarctica [*Rignot*, 1998; *Thomas et al.*, 2004]. Basal melting of ice shelves resulting from flow of relatively warm Circumpolar Deep Water onto the continental shelf may have triggered these changes [*Jacobs et al.*, 1996; *Shepherd et al.*, 2004]. The marine and terrestrial records of change in the Amundsen Sea region during the Quaternary (the past 1.8 million years) are key to understanding the stability and climate sensitivity of the WAIS, which in turn is essential to refining ice sheet models and thus improving predictions of the contribution from

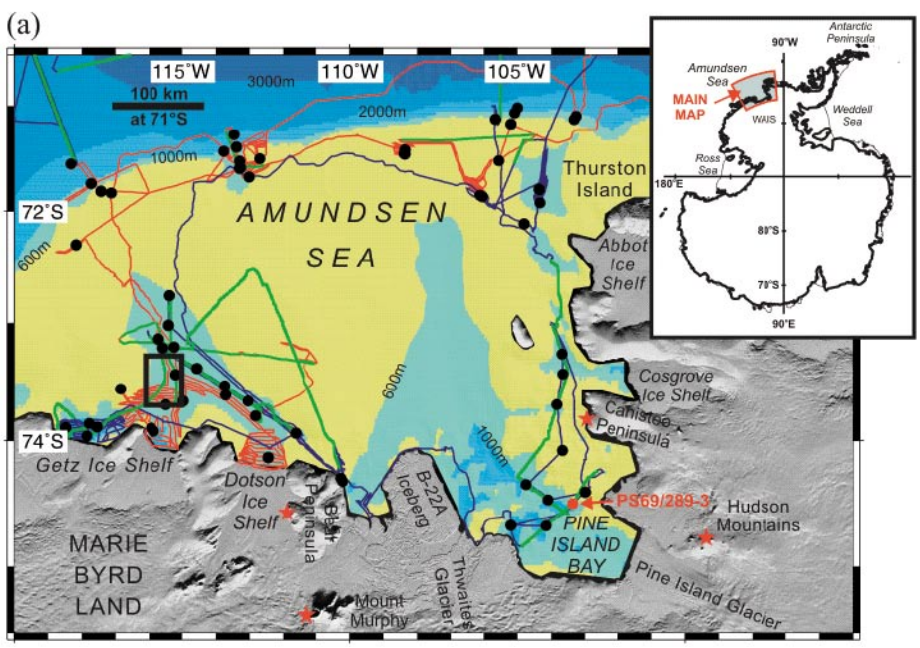
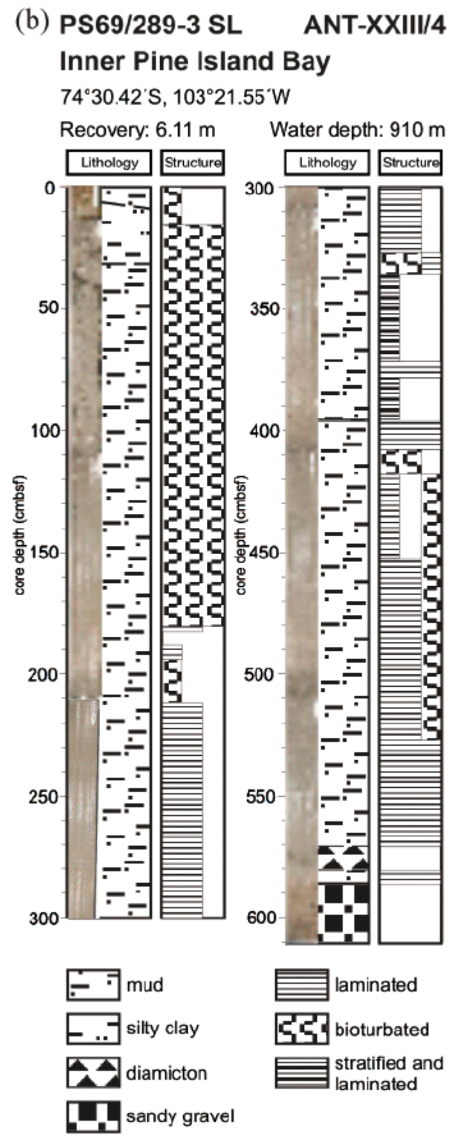


Fig. 1. (a) Map showing tracks of 2006 research cruises (red, RRS James Clark Ross*; blue, R/V* Polarstern*), seismic lines (green), core sites (black dots and one red dot) and sites sampled for surface exposure age dating (red stars) in the Amundsen Sea embayment. Color background is regional bathymetry, from a new compilation of echo sounding data* [Nitsche et al., *2006]. Black box indicates location of Fig. 2. Grayscale imagery shown over onshore areas is part of the MODIS Mosaic of Antarctica (courtesy of National Snow and Ice Data Center).*



(b) Photographs (left-hand column), lithological and sedimentary structure logs of core PS69/289-3 collected in Pine Island Bay. Core location is shown by red dot in Figure 1a.

Antarctica to global sea level rise. In the latest Intergovernmental Panel on Climate Change (IPCC) Summary for Policymakers, model projections of sea level rise exclude the effects of future rapid dynamical changes in ice flow "because a basis in published literature is lacking" [*IPCC*, 2007].

Records of changes in the WAIS during late Quaternary deglaciations, particularly since the Last Glacial Maximum (LGM, ~20,000 years ago), can be used to test and refine such models. Extensive new data on the late Quaternary history of the WAIS were collected during two research cruises to the Amundsen Sea embayment that took place in January–April 2006 (Figure 1a). The expeditions were closely coordinated by scientists from the British Antarctic Survey (BAS) and the Alfred Wegener Institute for Polar and Marine Research (AWI), Germany.

Previous Quaternary Research

Even though about one third of the outflow from the WAIS is into the Amundsen Sea, little is known about the history of the major glacial systems in this area. A reconstruction of ice retreat since the LGM has been proposed for Pine Island Bay (Figure 1a), but it is based on a small number of radiocarbon dates with large uncertainties [*Lowe and Anderson*, 2002].

Few vessels visit the Amundsen Sea embayment because of its remoteness and persistent sea ice cover. Multibeam echo-sounding data collected on the only research cruise to the region in the five years before the 2006 expeditions revealed streamlined subglacial bed forms within a bathymetric trough on the continental shelf at 114°W, suggesting that the WAIS grounding line advanced to the shelf edge during the last glaciation [*Evans et al.*, 2006]. A cross-shelf trough along 107°W containing similar bed forms and extending at least as far north as 72°S has also been described from earlier data collected on the R/V *Nathaniel B. Palmer* [*Lowe and Anderson*, 2002]. The relationship between the two troughs remains unclear.

New Data

In early 2006, successive research cruises on the RRS *James Clark Ross* (cruise JR141, January–February) and the R/V *Polarstern* (expedition ANT-XXIII/4, February–April) visited the Amundsen Sea embayment. A compilation of previous echo-sounding data produced by the Lamont-Doherty Earth Observatory (and subsequently updated to include the new data [*Nitsche et al.*, 2006]) proved a valuable aid to planning. A comprehensive package of data that was transferred from the *James Clark Ross* to the *Polarstern* facilitated precise planning of additional survey work to cover complementary areas. Much of the work on both cruises was concentrated in a large polynya (open water area) in the western embayment and on the outer shelf and slope (Figure 1a). Guided by helicopter ice reconnaissance observations, the *Polarstern* broke through sea ice to reach another polynya in Pine Island Bay and along the eastern coast of the embayment.

On both cruises, extensive new sonar imagery (multibeam echo sounding of the seafloor and subbottom acoustic profile data), sediment cores, and high-resolution seismic reflection profiles were collected to examine late Quaternary glacial changes in the Amundsen Sea. Changes in the surface elevation of adjacent parts the WAIS since the LGM were also investigated by using the helicopters on the *Polarstern* to visit ice-free onshore sites and obtain samples for surface exposure age dating. Thus, the data sets collected should provide new constraints on changes in both the extent and surface elevation of the WAIS. GPS measurements were made to determine present-day flow velocities and tidal motion of several ice shelf sites. Oceanographic data collected on both cruises will provide constraints on the modern water circulation in the embayment.

The new surveys more than double the spatial coverage of detailed bathymetric data on the continental shelf and reveal streamlined subglacial bed forms (Figure 2), allowing reconstruction of the paleo-ice drainage pattern during the last glaciation. Data collected north of the Dotson and Getz ice shelves indicate that three ice stream tributaries converged into a single main trunk, which then flowed northwestward across the shelf. A trough over 1600 meters deep north of the Getz Ice Shelf is the deepest yet found anywhere on the West Antarctic continental shelf. The axes of the deepest troughs in this area form a dendritic pattern with meanders and undulating depths, features that have been interpreted elsewhere as being indicative of subglacial meltwater erosion [e.g., *Lowe and Anderson*, 2002].

Multibeam data collected over the outer shelf mostly show randomly oriented trails produced by iceberg keels plowing through the sediments. However, bed forms of likely subglacial origin, exhibiting a strong preferential alignment in a northeast to north-northeast direction, were observed in two previously unmapped troughs on the eastern part of the outer shelf.

The sediment cores collected (locations in Figure 1a) will provide new insights regarding past subglacial processes on the continental shelf, paleoenvironmental changes associated with deglaciation, and the timing of the last deglaciation. A vibrocorer used on the *James Clark Ross* recovered a total of 130 meters of core from 39 sites on the continental shelf and upper slope. On the *Polarstern*, a gravity corer recovered a total of 92 meters from 24 sites, including three cores exceeding 9 meters in length collected from deep troughs in Pine Island Bay (Figure 1b). Cores from the outer shelf and the upper slope typically contain a subglacial, deglacial, and Holocene (the past 10,000 years of the current postglacial period of time) succession from soft, massive diamicton (nonsorted conglomerates of glacial sediment) at the base, through gravelly and sandy mud to bioturbated mud with upward increasing contents of planktonic foraminifera. The succession from inner shelf sites is similar, but with diatoms as the dominant microfossils.

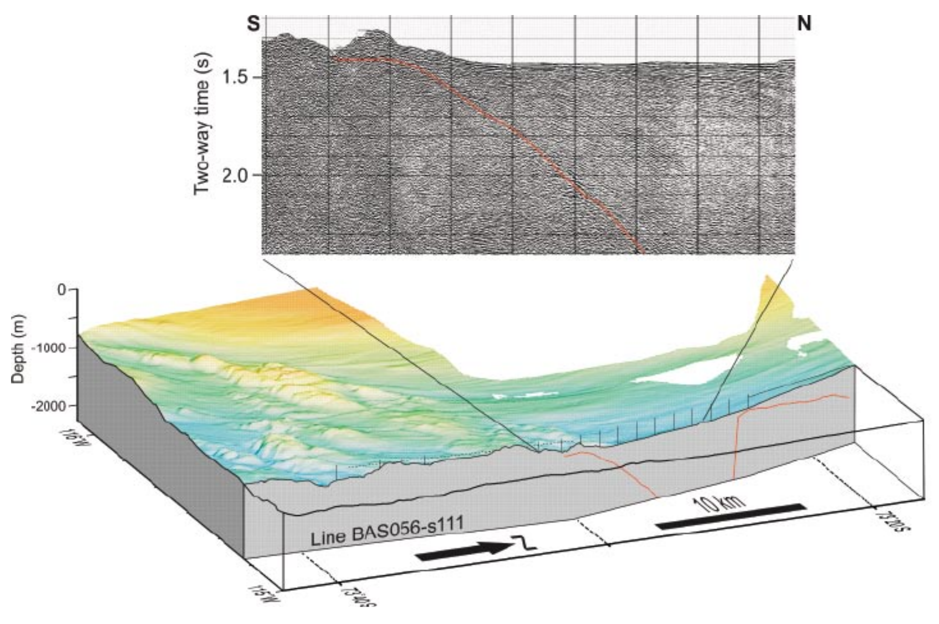


Fig. 2. Perspective view of multibeam echo-sounding data showing change in seafloor morphology, from drumlins (elongated hills formed by glacial activity) on left to megascale glacial lineations on right, along the course of a paleo-ice stream. The front of the block diagram is transparent to show the position of a seismic reflection profile (shaded light gray) running through the area. Red lines on the seismic profile mark the top of acoustic basement. The change in seafloor morphology coincides with a transition in substrate, from acoustic basement to sedimentary strata. Inset shows data on part of the seismic profile.

We will use the new marine data to reconstruct the retreat of the ice sheet since the LGM. The timing of deglaciation will be largely determined using radiocarbon techniques once we have established a regional marine reservoir correction from seafloor sediments sampled with box corers. The measurement of radiocarbon ages of calcareous foraminifera from the outer shelf sediments will allow assessment of the offset between ages measured on carbonate and on organic carbon.

To fully reconstruct the deglaciation, it is also important to obtain data on changes in ice surface elevations. Samples were collected from glacially derived erratic boulders (rocks that have been transported to a new location by glaciation) found on bedrock surfaces at four sites (Figure 1a). Granitoid erratics were commonly found. Quartz extracted from these samples will be analyzed for concentrations of beryllium-10 and aluminum-26, isotopes produced when cosmic rays penetrate the boulders, splitting apart atomic nuclei within the rock. The isotopic abundance indicates how long ago ice last covered the rock surfaces.

High-resolution seismic reflection profiles (Figure 1a) will allow assessment of the variability of glacial processes on the shelf over several glacial cycles, and also allow evaluation of the influence of substrate on ice dynamics. Profiles across the outer shelf will enable identification of buried troughs that were the paths of paleo-ice streams, and show whether they changed position during successive glacial periods. Preliminary examination of profiles across the inner shelf already show a transition from acoustic basement (crystalline or deformed sedimentary rocks) nearshore to undeformed sedimentary strata farther offshore that broadly correlates with a change in seafloor bed forms. These preliminary observations are consistent with the idea that substrate was an important control over the type of seafloor morphological features formed [*Wellner et al.*, 2001].

On the *Polarstern* cruise, deep-penetration reflection and refraction/wide-angle seismic data, as well as gravity and extensive shipborne and helicopter magnetic data, were also collected to investigate the crustal structure of the Amundsen Sea embayment. These data will provide a basis for considering how structural elements influenced growth and retreat of the ice sheet through controls on topography and the disposition of sedimentary basins.

Future Research

Despite the collection of these extensive new data, much more remains to be done in the Amundsen Sea embayment, particularly on the central part of the shelf that remained covered by pack ice throughout the 2005–2006 austral summer and onshore studies. Complete reconstruction of LGM paleo-ice streams will require much more extensive bathymetric data coverage. The continental shelf in the embayment is about 100,000 square kilometers in area, comparable in size to the state of Colorado, and the total area covered so far is only about 20% of that.

Acknowledgments

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Author Information

Tara Deen, Claus-Dieter Hillenbrand, Joanne Johnson, Rob Larter, Roy Livermore, and James Smith, British Antarctic Survey, Cambridge, U.K.; E-mail: r.larter@bas.ac.uk; Graeme Eagles, Karsten Gohl, Gerhard Kuhn, Hans-Werner Schenke, and Gabriele Uenzelmann-Neben, Alfred Wegener Institute, Bremerhaven, Germany; Frank Nitsche, Lamont-Doherty Earth Observatory of Columbia University, Palisades, N.Y.; Carol Pudsey, University of Dundee, U.K.; Reinhard Dietrich, Technical University Dresden, Germany; and Gleb Udintsev, Vernadsky Institute for Geochemistry, Moscow.