Recent advances in understanding Antarctic climate evolution

Martin J. Siegert[1], P. Barrett[2], R. DeConto[3], R. Dunbar[4], C. Ó Cofaigh[5], S. Passchier[6] and T. Naish[2,7]

[1]School of GeoSciences, University of Edinburgh, UK; m.j.siegert@ed.ac.uk; [2]Antarctic Research Centre, Victoria University of Wellington, New Zealand; [3]Department of Geosciences, University of Massachusetts, USA; [4]Department of Geological and Environmental Sciences, Stanford University, USA; [5]Department of Geography, Durham University, UK; [6]Department of Earth and Environmental Studies, Montclair State University, USA; [7]Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand

Geological evidence shows that the ice sheet and climate in Antarctica has changed considerably since the onset of glaciation around 34 million years ago. By analyzing this evidence, important information concerning processes responsible for ice-sheet growth and decay can be determined, which is vital to appreciating future changes in Antarctica. Here, we document five distinct case studies as examples of recent insights into Antarctic climate evolution.

The extent of the Antarctic ice sheet (AIS) has fluctuated considerably during its ~34 million year existence, and has been a major driver of changes in global sea level and climate throughout the Cenozoic Era. The spatial scale and temporal pattern of these fluctuations has been the subject of considerable debate. Determination of the scale and rapidity of the response of large ice masses and associated sea-ice to climatic forcing is of vital importance. Ice-volume variations lead to both changes in global sea levels—on a scale of tens of meters or more—and in alteration in the capacity of ice sheets and sea-ice as major heat sinks, insulators and reflectors. It is thus important to assess the stability of the cryosphere under a warming climate (IPCC, 2001). Here we assess five areas of activity, which, when combined, provide a means of gauging the variety of activities needed to gain a fuller appreciation of Antarctic glacial history.

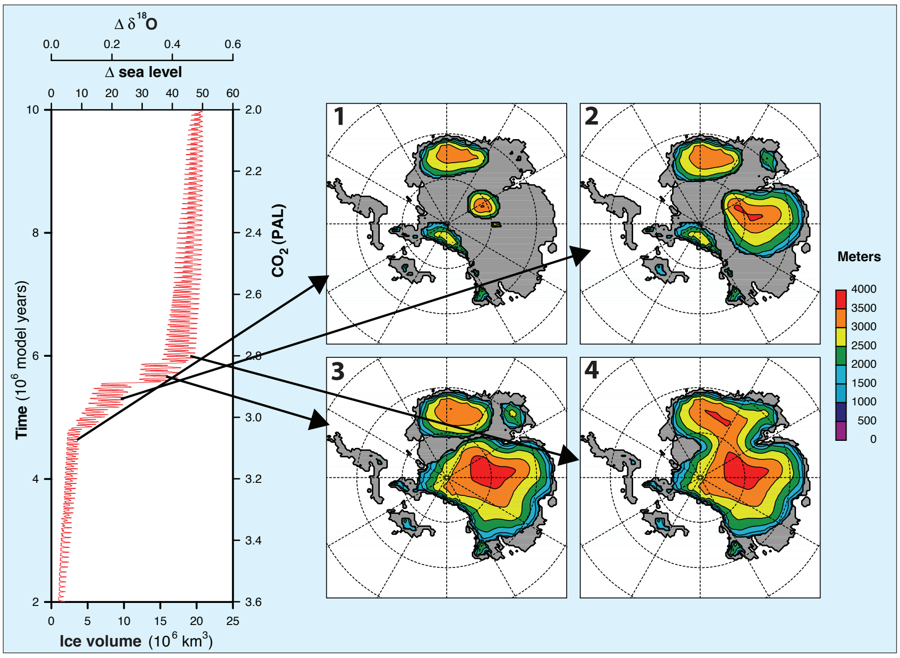

*Figure 1: Ice volume (**left**) and corresponding ice sheet geometries (**right**) simulated by a coupled atmospheric general circulation - ice sheet model, in response to a slow decline in atmospheric CO$_2$ (modified from DeConto and Pollard, 2003).*

CO$_2$ and ice-sheet inception at the Eocene-Oligocene boundary

While the onset of continental-scale glaciation in the earliest Oligocene (Oi-1 event; ~34 Myr) has long been attributed to the opening of Southern Ocean gateways (Kennett, 1977), recent numerical modeling studies suggest declining atmospheric CO$_2$ was the most important factor in Antarctic glaciation. As the passages between South America and the Antarctic Peninsula (Drake Passage), and Australia and East Antarctica (Tasmanian Passage) widened and deepened during the late Paleogene and early Neogene, the southern oceans experienced cooling sea surface temperatures by several degrees. Estimates for the opening of Drake Passage range between 40 and 20 Myr, blurring the direct 'cause and effect' relationship between the gateways and earliest glaciation.

To help solve this issue, coupled climate-ice sheet models have simulated the Eocene-Oligocene boundary accounting for decreasing CO$_2$ concentrations and orbital variability (DeConto and Pollard, 2003). Results from the modeling show that tectonically-forced changes in ocean circulation and heat transport have only a small effect on temperature and glacial mass balance in the Antarctic interior. Considering the sensitivity of polar climate to the range of CO$_2$ concentrations predicted to have existed over the Paleogene-Neogene, CO$_2$ likely played a fundamental role in controlling Antarctica's climate. Modeling also revealed that the timing of glaciation in East Antarctica is sensitive to orbital forcing, mountain uplift, and continental vegetation, but only within a very narrow range of atmospheric CO$_2$ concentrations—around 2.8 times modern levels. Once a CO$_2$ threshold is approached, astronomical forcing triggers the growth of a continental-scale ice sheet within 100 kyr (Fig. 1).

Orbital control on ice-sheet dynamics at the Oligocene-Miocene boundary

Drilling off the Antarctic margin at Cape Roberts has revealed 55 sedimentary cycles recording advance and retreat of the ice margin sea-level changes. Two of the cycles contain volcanic ash whose ages link them with particular Milankovitch cycles 24 and 24.2 Myr in the deep-sea isotope record (Naish et al., 2001). Analysis of deep-sea isotope records indicate sea level variations of 30-60 m from changes in ice sheet volume at this time. The sediments also show that the Antarctic coastal temperature declined progressively through Oligocene and early Miocene time, which is at odds with a major shift of the δ^{18}O values at ~25 Myr, interpreted previously as a warming of the oceans.

Coring of the Antarctic margin will continue over the next two years in nearby McMurdo Sound, where two 1000-m-deep holes will be cored by ANDRILL, to cover the time interval from the present back to 10 Myr and from 10-20 Myr. Together with the Cape Roberts core, this will provide an unprecedented paleoenvironmental record for this part of the Antarctic margin for the last 34 Myr.

Neogene major expansions and retreats of the EAIS

The Lambert Glacier is the largest fast-flowing outlet glacier in the world, draining ~12% of the East Antarctic Ice Sheet (EAIS) into Prydz Bay. During advances of the Lambert Glacier to the shelf break, glaciogenic material is deposited on nearby mountains. Formations in the Prince Charles Mountains were laid by fast-flowing polythermal tidewater glaciers analogous to those of the modern fjords of East Greenland, with ages ranging from early Miocene (or possibly Oligocene) to Pliocene-Pleistocene. Numerical modeling studies of erosion and sediment supply suggest that, besides climate, continued excavation and overdeepening of the glacial trough during ice advance phases is an important factor controlling the dynamics of the Lambert Glacier (Taylor et al., 2004).

Synchronicity of late deglacial ice retreat in Antarctica

The retreat of Antarctica's ice sheet following the Last Glacial Maximum (LGM) has been studied for more than 30 years, through marine geology and continental glacial geomorphology, yet many questions remain regarding the timing, speed, and style of ice retreat. New coring capabilities, as well as refinements in age-dating methods, are yielding surprising results regarding the timing of last deglacial ice retreat off Antarctica's continental shelf. Long sediment cores have been collected from both sides of the Antarctic Peninsula, the Ross Sea and distant regions of the East Antarctic continental shelf. By dating the biogenic sediments immediately overlying LGM diamict (poorly sorted sediment), it is possible to estimate the timing of ice retreat from outer and mid-shelf regions. The developing view is of rapid and synchronous retreat of ice from widely separated regions of Antarctica's continental shelf beginning at ~11.5 cal kyr BP and lasting for up to 800 years. This apparent synchronicity is unexpected, given previous inferences of large geographic asynchronicity in the timing of maximum glacial advance and subsequent early deglacial history (Anderson et al., 2002).

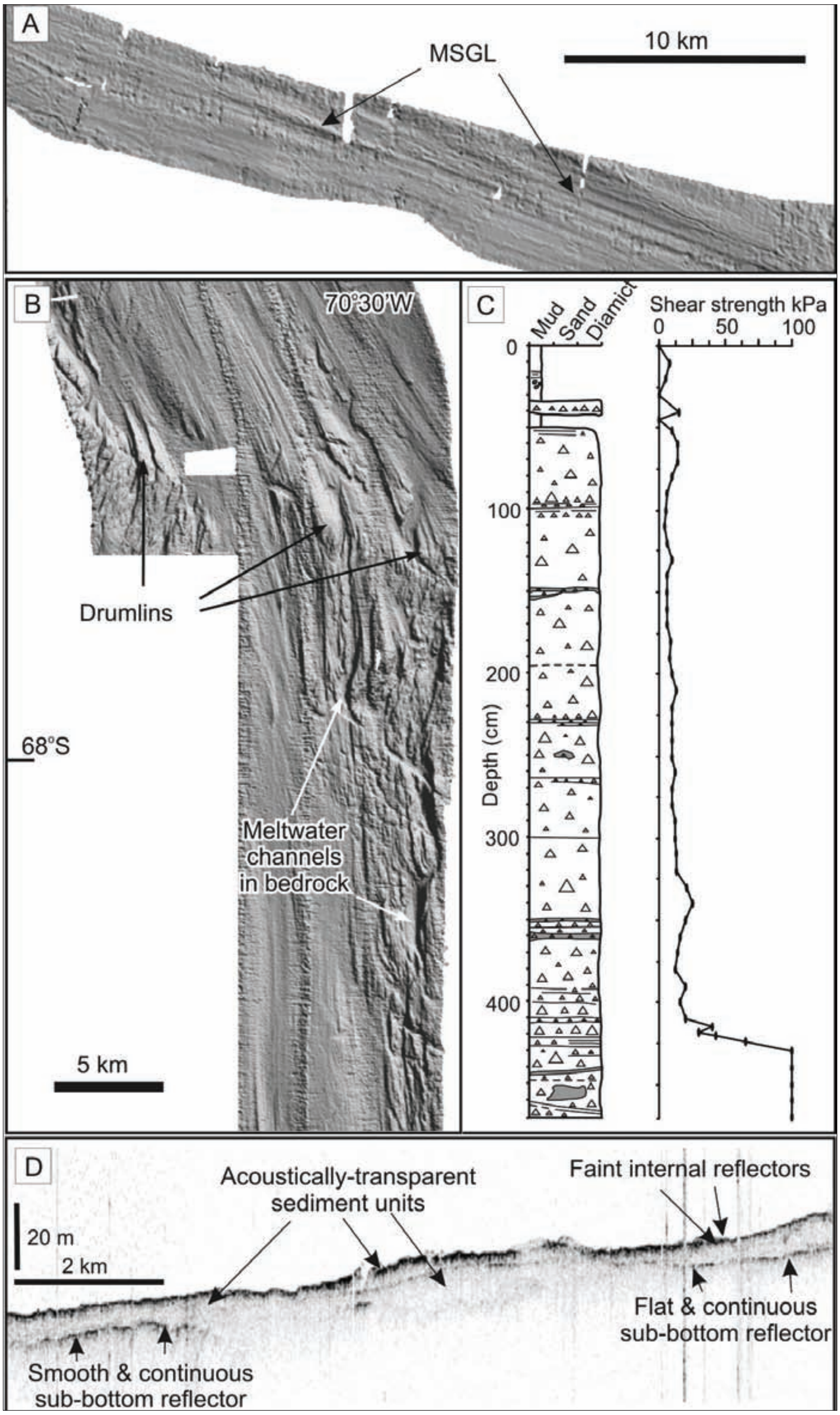

Figure 2: Geophysical and geological records of paleo ice-stream flow in bathymetric troughs on the Antarctic continental shelf. ***A****) Swath bathymetry shaded relief image of mega-scale glacial lineations (MSGL) at the mouth of the Ronne Entrance, Bellingshausen Sea;* ***B****) Swath bathymetry showing sea-floor morphology as a shaded relief image in middle-outer Marguerite Trough, Antarctic Peninsula;* ***C****) Core log and shear strength plot of sub-ice stream sediments, Marguerite Trough;* ***D****) TOPAS sub-bottom profiler record from the Ronne Entrance showing acoustically transparent sediment unit (soft till) sitting above a prominent basal reflector (arrowed).*

Subglacial processes and flow dynamics of former Antarctic ice streams

Recent marine geophysical and geological research from the Antarctic continental shelf has significantly advanced our understanding of the extent and dynamics of the Antarctic Ice Sheet (AIS). During the LGM, the AIS was positioned at, or close to, the shelf edge around the Peninsula, the Bellings-hausen Sea and Pine Island Bay. In these areas, large glacial troughs extend across the continental shelf, and sedimentary and geomorphic evidence from these troughs (Fig. 2a,b) indicate that they were occupied by grounded paleo ice streams during, or immediately following, the LGM (Ó Cofaigh et al., 2002). Mega-scale glacial lineations (subglacially produced ridges) can attain lengths of greater than 20 km within the troughs and are characteristically formed in a weak porous and deformable till layer (Fig. 2c,d). Such weak tills have been identified and mapped in all the paleo ice-stream troughs investigated to date. They tend to be confined to the troughs and are not widely observed in the inter-trough areas. The association of this weak porous till layer with highly elongate subglacial bedforms implies that the rapid motion of these ice streams was facilitated, at least in part, by subglacial deformation of the soft bed. Geophysical data also indicate significant transport of subglacial till towards the former ice-stream terminus. The implication that paleo Antarctic ice streams were underlain by weak sediments is indicative of a dynamic, fast-flowing ice sheet at the LGM, much like it is today in West Antarctica, allowing rapid ice-sheet responses to sea level and ocean temperature changes.

Future activities

Although our appreciation of Antarctic history has improved dramatically over the past decade, there is still much to learn. Significant questions exist about the evolution of Antarctic landscape, both above and below the ice cover; its connection with ice-sheet development; past and present large-scale ice-sheet dynamics and stability; the role of sub-glacial water in the ice-sheet system; and the influence of ice-sheet evolution on Antarctic biology. In 2004, the Scientific Committee on Antarctic Research (SCAR) recognised the importance of understanding past changes in Antarctica with the establishment of its Antarctic Climate Evolution (ACE) scientific research program. This program, in conjunction with other SCAR program's (SALE – Subglacial Antarctic Lake Environments; AGCS – Antarctica in the Global Climate System; and EBA – Evolution and Biodiversity in Antarctica), aims to further integrate numerical models with geological data, in order to understand the processes responsible for the growth and decay of large ice sheets and to comprehend the global significance of such changes.

Acknowledgements

We thank the committee and members of the ACE program (www.ace.scar.org) for helpful input and advice.

References

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S. and Mosola, A.B., 2002: The Antarctic ice sheet during the last glacial maximum and its subsequent retreat history: a review, *Quaternary Science Reviews*, **21**: 49-70.

DeConto, R.M. and Pollard, D., 2003: Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2, *Nature*, **421**: 245-249.

Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S. and 29 others, 2001. Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene-Miocene boundary, *Nature*, **413**: 719-723.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell J.A. and Morris, P., 2002: Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf, *Geophysical Research Letters*, **29**: 10.1029/2001GL014488.

Taylor, J., Siegert, M.J., Payne, A.J., Hambrey, M.J., O'Brien, P.E., Cooper, A.K. and Leitchenkov, G., 2004: Topographic controls on post-Oligocene changes in ice-sheet dynamics, Prydz Bay region, East Antarctica, *Geology*, **32**: 197–200.

For full references please consult:
www.pages-igbp.org/products/newsletter/ref2007_2.html

Antarctic ice cores

Eric Wolff[1] **and Edward Brook**[2]

[1]British Antarctic Survey, Cambridge, UK; ewwo@bas.ac.uk; [2]Deptartment of Geosciences, Oregon State University, Corvallis, USA

Terrestrial and marine paleoclimate records are very sparse in the southern hemisphere, particularly at high latitudes. However, this is where ice cores come into their own. Antarctic ice cores provide a firm and well-resolved anchor for our understanding of how climate has evolved over 800 kyr, and provide climate information for assessing how the Antarctic Ice Sheet may have varied over the same period. They are also the best archive for determining the history of greenhouse gas concentrations and offer unique data on other important forcings, such as volcanic aerosol and solar.

Characteristics of Antarctic ice cores

Almost the whole of the Antarctic ice sheet fulfils the basic requirements for good ice core records, namely that snow is laid down in regular layers without significant loss or percolation by melting. In near coastal areas, relatively high snow accumulation rates allow the collection of records for which annual layer counting is possible. This is the area of choice for well-resolved and precisely dated records of recent centuries. In central regions of the Antarctic plateau, the ice is very thick (~3 km) but the snow accumulation rate may be as low as 2 cm water equivalent. It is in this region that records extending back over hundreds of thousands of years can be found, although the dating is necessarily less precise.

The water isotopes in the ice act as a good proxy of Antarctic temperature and also provide information on conditions over the ocean (the source of the water vapor). Due to the low impurity content of the ice, Antarctic cores are well suited to analysis of trace gases, and the chemical content provides information about environmental conditions in the Southern Ocean and other southern continents.

Recent centuries

As atmospheric measurements of greenhouse gases have only been carried out routinely for, at most, a few decades, ice cores have for some time been relied upon to show how greenhouse gas concentrations increased during the past two centuries, and how they varied in the preceding period. A new study (MacFarling Meure et al., 2006) has extended the period of high-resolution to 2 kyr, expanded the high-resolution work from CO_2 and CH_4 to include N_2O, and filled in gaps in the previous records. Together with the existing data and other data from sites with lower-resolution that confirm most of the details, this work provides a definitive account of greenhouse gas variability and trend; it is indeed

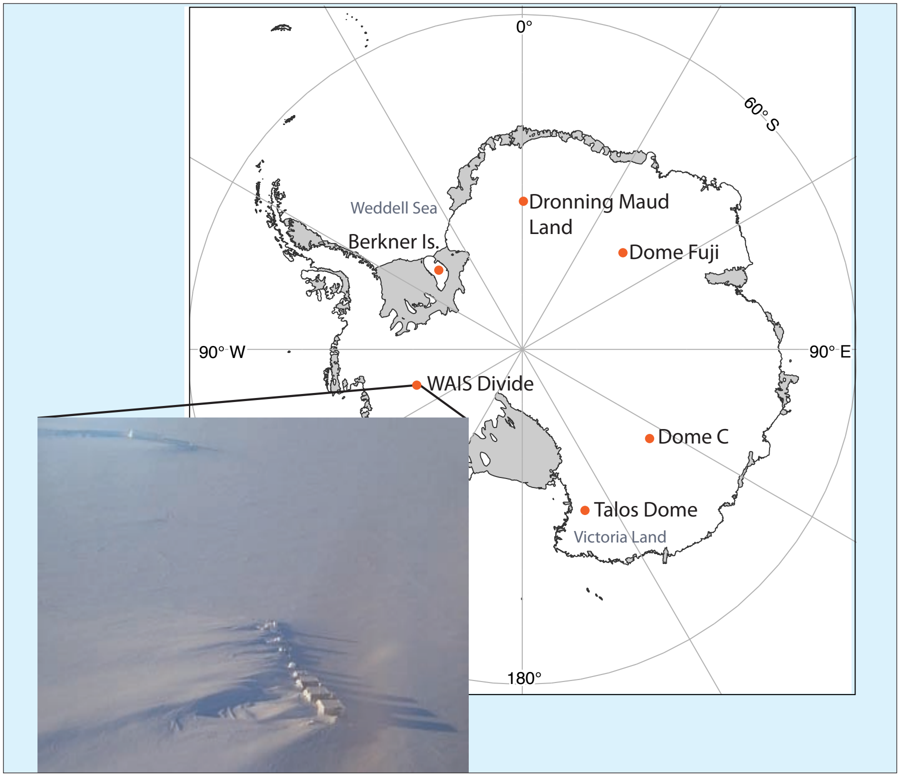

Figure 1: Map of cores and locations mentioned in text. ***Inset****: photo of WAIS Divide site, with camp in center and drilling site top left corner (E. Brook).*