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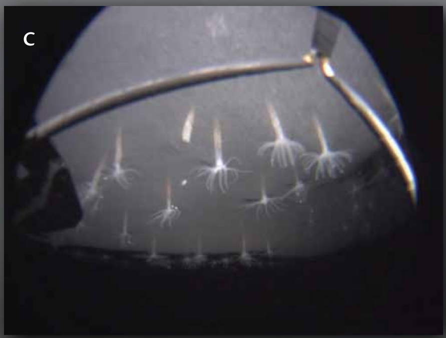
What Lies Beneath?

Interdisciplinary Outcomes of the ANDRILL Coulman High Project Site Surveys on the Ross Ice Shelf

BY FRANK R. RACK, ROBERT ZOOK, RICHARD H. LEVY, RICHARD LIMEBURNER, CRAIG STEWART, MICHAEL J.M. WILLIAMS, BRUCE LUYENDYK, AND THE ANDRILL COULMAN HIGH PROJECT SITE SURVEY TEAM

ABSTRACT. Extensive field operations were conducted on the northwestern Ross Ice Shelf in Antarctica from November 2010 through January 2011. A significant amount of equipment, supplies, and people safely traversed from McMurdo Station to establish a series of combined United States–New Zealand field camps at locations northeast of Ross Island. The ANDRILL (ANtarctic geological DRILLing) hot water drill system was used to melt multiple access holes through the ice shelf at each site to deploy a variety of sediment coring tools, cameras, and oceanographic instruments, as well as a remotely operated vehicle to characterize the ice shelf and sub-ice environment. These studies will contribute to future proposed geological drilling as part of the ANDRILL Coulman High Project.



(a) SCINI (Submerible Capable of under-Ice Navigation and Imaging) remotely operated vehicle with improvised suction sampling device used to recover biological samples from the bottom of the Ross Ice Shelf. (b) Anemones recovered in a small coffee filter within the improvised sampling device. (c) View from the SCINI forward camera across the bottom of the Ross Ice Shelf showing anemones (~ 5 cm long) living inside the ice and feeding in the boundary layer at the ice shelf-ocean interface. (d) View from SCINI's forward fisheye lens showing an unknown organism, nicknamed the "eggroll," hanging onto an anemone to maintain position in a current—the creature seems to have appendages at both ends and is about 10–15 cm long.

INTRODUCTION

Understanding the behavior of Antarctic ice sheets during past periods of global warmth and times of higher-than-present levels of atmospheric CO_2 is key to predicting the future response of ice sheets and ice shelves to projected global change. Geological archives preserved in sediment and rock cores from the Antarctic margin provide the only direct records of past ice sheet variability during these past periods of warmth (Naish et al., 2009; Pollard and DeConto, 2009). ANDRILL (ANtarctic geological DRILLing) aims to obtain such geological archives to provide basic paleogeographic and paleoclimatic constraints to enhance numerical climate and ice sheet models that allow a better understanding of ice sheet response to climate variability. Current efforts within the ANDRILL program seek to move operations east of Ross Island to the Ross Ice Shelf overlying Coulman High (CH) and develop the capability to drill from a fast-moving ice shelf platform (~ 700 m yr^{-1} or ~ 2 m day^{-1}).

The primary geologic target for the proposed Coulman High Project (CHP) is a sequence of sedimentary rocks deposited between > 45 and 20 million years ago that record the history of tectonic extension, subsidence, and uplift, as well as glacial and climate history (Wilson and Luyendyk, 2006, 2009; Decesari et al., 2007; Wilson et al., 2012). Drilling targets were selected along a marine multichannel seismic line (MCS) acquired by RVIB *Nathaniel B. Palmer* in front of the ice shelf in 2003 (Decesari, 2006) after a series of large icebergs, including the C19 iceberg that broke away from the Ross Ice Shelf during 2000–2002 (Arrigo and van Dijken, 2003). Since then, the ice shelf has advanced northward and now covers the target seismic line NBP0301-1A0 where two sites (CH-1 and CH-2) have been selected for drilling (Figure 1). These sites should record a history of Antarctica during the transition from a "greenhouse world" when global atmospheric temperatures were 4–6°C warmer than present and atmospheric CO_2 levels were at least twice pre-industrial levels (i.e., 600 ppmv and possibly much higher; IPCC, 2007).

FIELD SURVEYS

Extensive field surveys were conducted in Antarctica from November 2010 through January 2011 as part of the proposed ANDRILL CHP (Figure 1). A significant amount of equipment, supplies, and people safely traversed approximately 120 miles from McMurdo Station to establish a series of combined United States-New Zealand field camps on the Ross Ice Shelf at locations northeast of Ross Island (Figure 2a,b). The ANDRILL

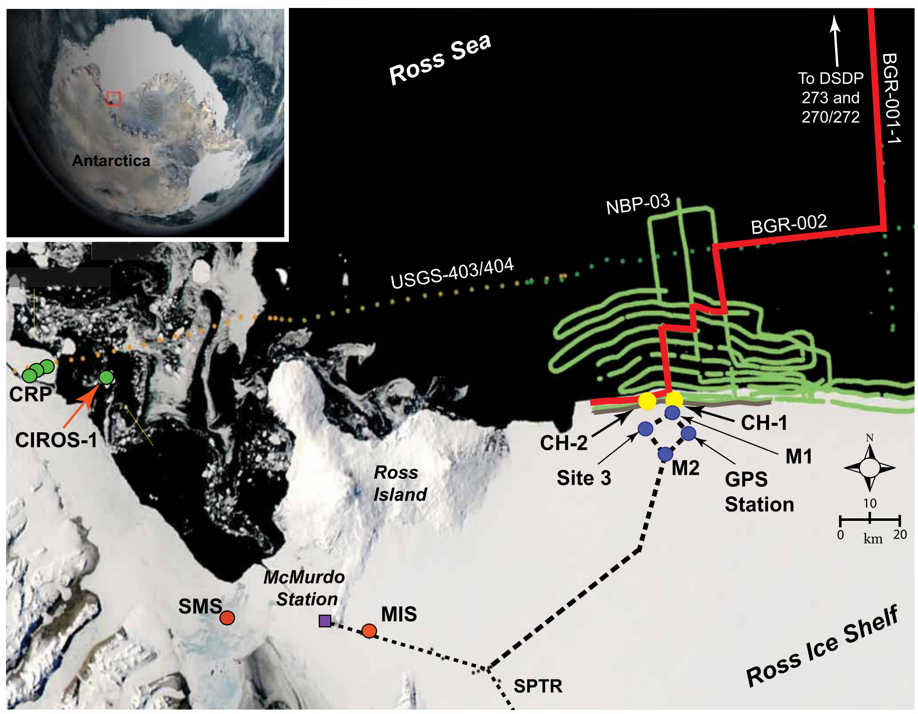


Figure 1. (Inset) Ross Sea region, Antarctica. This map shows the location of McMurdo Station on Ross Island, Antarctica, the traverse route to the ANDRILL (ANtarctic geological DRILLing) Coulman High Project (CHP) survey area northeast of Ross Island (dashed lines), and the site locations described in the text: CH-1 and CH-2 (yellow circles) are the two proposed CHP drill sites (on seismic line NBP0301-1A0); M1 and M2 (light blue circles) are the two oceanographic moorings. At Site 3 (blue circle), various oceanographic instruments and the SCINI remotely operated vehicle were repeatedly deployed over several days. GPS stations were deployed at each corner of the diamond marked by the four blue circles. The figure also shows the locations of prior scientific drilling in Southern McMurdo Sound, including the ANDRILL drill sites (red circles) from the McMurdo Ice Shelf (MIS) and Southern McMurdo Sound (SMS) projects, and the earlier Cape Roberts Project (CRP) and Cenozoic Investigation in the Western Ross Sea (CIROS)-1 drilling (green circles) conducted from sea ice platforms. Marine seismic survey lines (green) were collected by the NBP-03-01 cruise on RVIB *Nathaniel B. Palmer* over Coulman High in 2003 (Decesari, 2006; Decesari, et al., 2007) following the calving of the C-19 iceberg in 2002; correlation paths to Deep Sea Drilling Project (DSDP) and CRP sites are indicated. Seismic lines collected by the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) are in red, and the small colored dots are locations of US Geological Survey seismic lines USGS-403/404.

hot water drill system (Figure 2c,d) was used to melt 10 to 60 cm diameter access holes through 250–275 m of ice shelf at each site to deploy a variety of sediment coring tools, cameras, and oceanographic instruments, as well as a remotely operated vehicle (ROV) named SCINI (Submersible Capable of under-Ice Navigation and Imaging; Cazenave et al., 2011). GPS stations were established at four sites to monitor lateral and vertical ice motions, and a weather station was set up at Site M1 to monitor environmental conditions (Figure 1). The weather featured fairly consistent winds out of the south that calmed during the last half of December 2010 and the first half of January 2011. Low overcast or fog was often present in this time interval, which proved to be a hindrance to helicopter access.

Oceanographic moorings were deployed at two sites perpendicular to the ice edge for at least two full tidal cycles (Figures 1 and 3; M1 = 55 days and M2 = 52 days). The M1 mooring, ~ 6 km south of the ice shelf edge, was the primary responsibility of the New Zealand National Institute of Water & Atmospheric (NIWA) research team, while the M2 mooring, ~ 17 km south of the ice shelf edge, was the primary responsibility of the team from Woods Hole Oceanographic Institution (WHOI). Each mooring was nominally comprised of a series of five temperature and conductivity loggers and five acoustic Doppler current profilers that were spaced throughout the water column during deployment (Figures 3 and 4). Data were recorded within each instrument and also transmitted to a surface inductive modem buried in the snow at the ice shelf surface to ensure that data could be easily accessed in case the moorings were not recovered. The M2 mooring had an Iridium satellite communications modem to transmit its data back to WHOI in near-real time during its deployment. The moorings were designed to measure tidal and ocean currents and water mass properties, to assess the environmental conditions in the sub-ice shelf ocean cavity, and to potentially serve as prototype ice shelf installations to contribute to the Southern Ocean Observing System (see Figure 31 in Rintoul et al., 2012). Oceanographic data acquired from the moorings indicate diurnal current variability with maximum speed up to 25 cm s^{-1}. Tidal harmonic analysis reveals that tides propagating around the ice shelf cavity cause ~ 50% of the current velocity variability (Williams and Robinson, 1980; MacAyeal, 1984a,b; Padman et al., 2003; Arzeno et al., 2012a,b). The data from these moorings will also be used to address the role of advection and mixing of water masses across the continental shelf and under the ice shelf (Holland et al., 2003; Dinniman et al., 2007, 2011; Orsi and Wiederwohl, 2009), especially when longer time-series measurements are available. The New Zealand mooring (M1) was reset after its initial two-month deployment to provide long-term observations under the Ross Ice Shelf; this mooring was still operating as of June 2012. The tidal current measurements and GPS data are being used to develop a tidal model for the drill site locations and to model the behavior of the ANDRILL sea riser to determine the most robust drilling strategy for the ANDRILL CHP.

Operations in each of the primary hot water drill holes included multiple deployments of a video camera, gravity corer, and a conductivity-temperature-depth (CTD) sensor. At Site 3 (Figure 1), there were multiple deployments of

Figure 2. Traverse vehicles and ANDRILL hot water drill system (HWDS). (a) Pisten Bully with ice-penetrating radar boom deployed. (b) Caterpillar D6 bulldozer traversing ANDRILL camp and HWDS modules. (c) MECC (Mobile Expandable Container Configuration) with floor hatch and work area for instrument deployments through the ice shelf. (d) ANDRILL HWDS modules, including hose reel, hot water boilers and pumps, and generators.

an acoustic Doppler current profiler and water samplers. These short-term deployments were meant to sample the water column and seafloor sediments, and observe the seafloor and the underside of the ice shelf. Video camera observations of the interior and basal surface of the Ross Ice Shelf were integrated with CTD profiles through the ice shelf and into the water column at several sites to better understand salinity and temperature gradients within the ice shelf borehole.

The SCINI ROV was deployed multiple times down a ~ 30 cm diameter hole at Site 3 and again near Site CH-1 (located ~ 10 and 6 km from the ice edge, respectively; Figure 1) to explore the underside of the ice shelf while conducting operational testing. Three ROV engineers/pilots deployed the vehicle for 29 hours spaced over 14 dives (Figure 5) with a maximum dive depth of ~ 300 m below mean sea level and a range of ~ 30 m around the ice hole. To our knowledge, this was the first time that an ROV was deployed through an ice shelf in Antarctica—and the results were phenomenal. Using the SCINI cameras, the WHOI team discovered and explored an unusual and possibly unique biological community dominated by anemones living inside burrows in the lower surface of the ice shelf, and

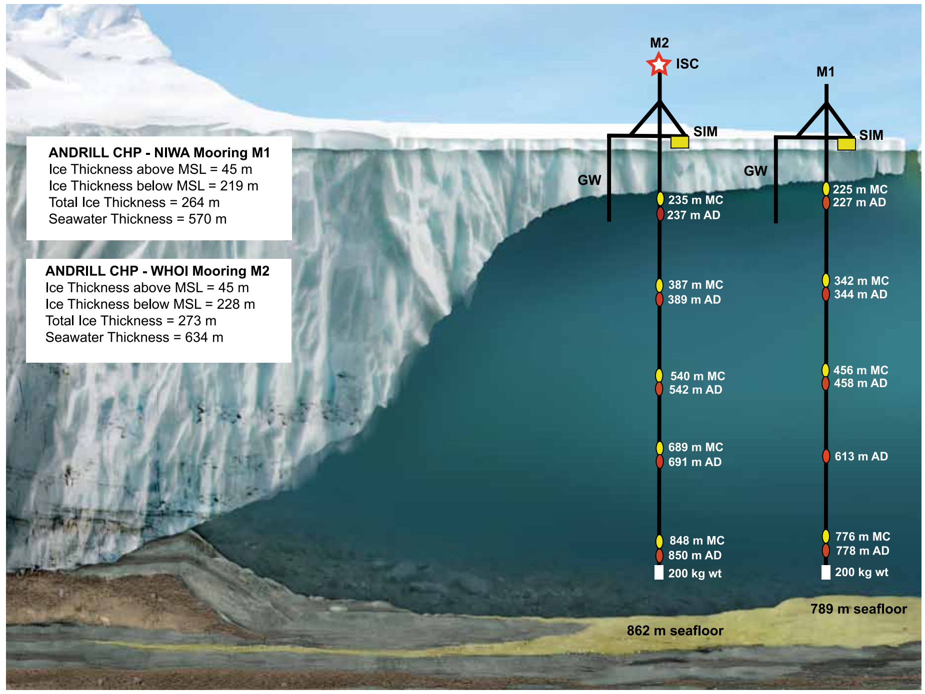


Figure 3. Schematic diagram (not to scale) of oceanographic moorings M1 (New Zealand National Institute of Water & Atmospheric Research, NIWA) and M2 (Woods Hole Oceanographic Institution), located 6 km and 17 km south of the ice front, respectively. These moorings were deployed through the Ross Ice Shelf for two months during 2010–2011. Five pairs of instruments equipped with inductive modems were deployed at each site at depths distributed through the water column below the ice shelf. GW = grounding wire. SIM = surface inductive modem (yellow box buried in snow). ISC = Iridium satellite communications (only at M2). Yellow ovals = Sea-Bird microcat (MC) temperature/salinity loggers. Red ovals = Nortek aquadop (AD) 6000 acoustic current meters).

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the ROV pilots recovered many biological samples using an improvised suction sampler (see photos on p. 84; Rack et al., 2011). These samples and extensive imagery, which are being further investigated, will provide preliminary information about the spatial distribution and nature of these organisms, as well as insights into the role of freezing and melting of ice (Horgan et al., 2012; Pritchard et al., 2012), advection of water masses and nutrients, and other influences on their life cycles and ecology.

Finally, an over-ice wide-angle and hydrophone seismic experiment was conducted using an array of geophones buried in the snow and a seafloor hydrophone, and other geophysical data (gravity) were collected along the ice surface extension of marine seismic line NBP03-1A0 to improve interpretations of existing marine seismic reflection data and finalize proposed CHP drill site selections.

Figure 4. Deployment of oceanographic instruments through the moonpool hatch in the MECC by NIWA (Craig Stewart, left) and WHOI (Will Ostrom) participants in the Coulman High Project. Personal harnesses were used to ensure safe operations around the ice hole.

SUMMARY REMARKS

The Ross Sea continental margin is recognized as a unique region of the Antarctic due to its broad continental shelf, significant polynyas, and extensive ice shelf (Smith et al., 2007). The unexpected biological discovery at the base of the Ross Ice Shelf highlights the importance of serendipity in science and points to the significant opportunities that interdisciplinary investigations can provide in these environments (NRC, 2011), as well as contributing to the establishment of an integrated Southern Ocean Observing System (Rintoul et al., 2012). The area northeast of Ross Island that is the focus of these studies provides an ideal location to establish a long-term monitoring station for physical and biogeochemical oceanography and ecology (focused on both macro- and microbiology). Using hot water drill holes to deploy or support an appropriate mixture of ice-tethered profilers, oceanographic moorings, camera systems, gliders, and remotely operated or autonomous underwater vehicles, the data gathered at this station will improve our understanding of this highly undersampled region, as does the work in McMurdo Sound and the Ross Sea (Gutt, 2001; Thrush et al., 2006; Kirchman et al., 2009; Griffiths, 2010; Kim et al., 2010; Schofield et al., 2010; Thrush and Cummings, 2011) as well as in other ice shelf regions around Antarctica such as the Amery Ice Shelf (Post et al., 2007). Geologic investigations of the long-term environmental and climatic history of this region can be integrated with interdisciplinary process studies and the development of proxies. These investigations can benefit from the sharing of logistical and operational planning to provide better science outcomes, as discussed in the report of the US Antarctic Program Blue Ribbon Panel (Augustine et al., 2012).

Figure 5. SCINI deployment team, left to right, Bob Zook, Paul Mahecek, and Dustin Carroll with the SCINI ROV. Note gripper at left end of the SCINI vehicle, aligned with the forward fisheye camera dome. During deployment through the ice shelf, a ballast weight was held in the gripper; it was later released to enable ROV operations.

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REFERENCES

Arrigo, K.R., and G.L. van Dijken. 2003. Impact of iceberg C-19 on Ross Sea primary productivity. *Geophysical Research Letters* 30(16):1,836–1,839, http://dx.doi.org/10.1029/2003GL017721.

Arzeno, I.B., R. Beardsley, B. Owens, R. Limeburner, L. Padman, M. Williams, C. Stewart, C. Lee, M. Dinniman, and S. Springer. 2012a. Tides under the Ross Ice Shelf front: Contributions to mixing and melting. Paper presented at the Ocean Sciences Meeting, Salt Lake City, UT, February 20–24, 2012, TOS/AGU/ASLO Abstract Book, p. 17.

Arzeno, I.B., R. Beardsley, B. Owens, R. Limeburner, L. Padman, M. Williams, C. Stewart, and C. Lee. 2012b. Looking under the Ross Ice Shelf: Tidal and subtidal variability. Paper presented at the Ocean Sciences Meeting, February 20–24, 2012 (Salt Lake City, UT), TOS/AGU/ASLO Abstract Book, p. 17.

Augustine, N.R., T. Allen, C.E. Dorman, H.W. Ducklow, B. Gordon, R. K. Harrison, D. Hartill, G. Jugie, L.J. Lanserotti, D.J. McNabb, and others. 2012. *More and Better Science in Antarctica through Increased Logistical Effectiveness, Report of the U.S. Antarctic Program Blue Ribbon Panel*. Study conducted at the request of the White House Office of Science and Technology Policy and the National Science Foundation, Washington, DC, 224 pp., http://www.nsf.gov/od/opp/usap_special_review/usap_brp/rpt/index.jsp.

Cazenave, F., R. Zook, D. Carroll, M. Flagg, and S. Kim. 2011. Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica. *The Journal of Ocean Technology* 6(3):39–58.

Decesari, R.C. 2006. The Mesozoic and Cenozoic depositional, structural, and tectonic evolution of the Ross Sea, Antarctica. PhD thesis, University of California, Santa Barbara.

Decesari, R.C., D.S. Wilson, B.P. Luyendyk, and M. Faulkner. 2007. Cretaceous and Tertiary extension throughout the Ross Sea, Antarctica. In *A Keystone in a Changing World—Online Proceedings of the 10th International Symposium on the Antarctic Earth Sciences*. A.K. Cooper, C.R. Raymond, and the 10th ISAES Editorial Team, eds, US Geological Survey Open File Report 2007-1047:098, http://pubs.usgs.gov/of/2007/1047/srp/srp098/of2007-1047srp098.pdf.

Dinniman, M.S., J.M. Klinck, and W.O. Smith Jr. 2007. Influence of sea ice cover and icebergs on circulation and water mass formation in a numerical circulation model of the Ross Sea, Antarctica. *Journal of Geophysical Research* 112, C11013, http://dx.doi.org/10.1029/2006JC004036.

Dinniman, M.S., J.M. Klinck, and W.O. Smith Jr. 2011. A model study of Circumpolar Deep Water on the West Antarctic Peninsula and Ross Sea continental shelves. *Deep Sea Research Part II* 58:1,508–1,523, http://dx.doi.org/10.1016/j.dsr2.2010.11.013.

Griffiths, H.J. 2010. Antarctic marine biodiversity—What do we know about the distribution of life in the Southern Ocean? *PLoS ONE* 5(8):e11683, http://dx.doi.org/10.1371/journal.pone.0011683.

Gutt, J. 2001. High latitude Antarctic benthos: A "coevolution" of nature conservation and ecosystem research? *Ocean and Polar Research* 23(4):411–417.

Holland, D.M., S.S. Jacobs, and A. Jenkins. 2003. Modelling the ocean circulation beneath the Ross Ice Shelf. *Antarctic Science* 15(1):13–23, http://dx.doi.org/10.1017/S0954102003001019.

Horgan, H.J., R.T. Walker, S. Anandakrishnan, and R.B. Alley. 2012. Surface elevation changes at the front of the Ross Ice Shelf: Implications for basal melting. *Journal of Geophysical Research* 116, C02005, http://dx.doi.org/10.1029/2010JC006192.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm.

Kim, S., K.K. Hammerstom, K.E. Conlan, and A.R. Thurber. 2010. Polar ecosystem dynamics: Recovery of communities from organic enrichment in McMurdo Sound, Antarctica. *Integrative and Comparative Biology* 50(6):1,031–1,040, http://dx.doi.org/10.1093/icb/icq058.

Kirchman, D.L., X.A.G. Moran, and H. Ducklow. 2009. Microbial growth in the polar oceans: Role of temperature and potential impact of climate change. *Nature Reviews Microbiology* 7:451–459, http://dx.doi.org/10.1038/nrmicro2115.

MacAyeal, D.R. 1984a. Thermohaline circulation below the Ross Ice Shelf: A consequence of tidally induced vertical mixing and basal melting. *Journal of Geophysical Research* 89(C1):597–606, http://dx.doi.org/10.1029/JC089iC01p00597.

MacAyeal, D.R. 1984b. Numerical simulations of the Ross Sea tides. *Journal of Geophysical Research* 89(C1):607–615, http://dx.doi.org/10.1029/JC089iC01p00607.

Naish, T., R. Powell, R. Levy, G. Wilson, R. Scherer, F. Talarico, L. Krissek, F. Niessen, M. Pompilio, T. Wilson, and others. 2009. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* 458:322–328, http://dx.doi.org/10.1038/nature07867.

NRC. 2011. *Future Science Opportunities in Antarctica and the Southern Ocean*. Committee on Future Science Opportunities in Antarctica and the Southern Ocean, National Research Council, The National Academies Press, Washington, DC, 195 pp.

Orsi, A.H., and C.L. Wiederwohl. 2009. A recount of Ross Sea waters. *Deep Sea Research Part II* 56:778–795, http://dx.doi.org/10.1016/j.dsr2.2008.10.033.

Padman, L., S.Y. Erofeeva, and I. Joughin. 2003. Tides of the Ross Sea and Ross Ice Shelf cavity. *Antarctic Science* 15(1):31–40.

Pollard, D., and R.M. DeConto. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* 458:329–332, http://dx.doi.org/10.1038/nature07809.

Post, A.L., M.A. Hemer, P.E. O'Brien, D. Roberts, and M. Craven. 2007. History of benthic colonization beneath the Amery Ice Shelf, East Antarctica. *Marine Ecology Progress Series* 344:29–37, http://dx.doi.org/10.3354/meps06966.

Pritchard, H.D., S.R.M. Ligtenberg, H.A. Fricker, D.G. Vaughan, M.R. van den Broeke, and L. Padman. 2012. Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* 484:502–505, http://dx.doi.org/10.1038/nature10968.

Rack, F., R. Levy, T. Falconer, R. Zook, P. Mahacek, D. Carroll, M. Williams, C. Stewart, R. Limeburner, and the ANDRILL Coulman High Project site survey team. 2011. Interdisciplinary outcomes of the ANDRILL Coulman High site surveys. P. 184 in *11th International Symposium on Antarctic Earth Sciences, Programme and Abstracts*. Edinburgh, Scotland, July 10–15, 2011.

Rintoul, S.R., M. Sparrow, M.P. Meredith, V. Wadley, K. Speer, E. Hofmann, C. Summerhayes, E. Urban, and R. Bellerby. 2012. *The Southern Ocean Observing System: Initial Science and Implementation Strategy.* Scientific Committee on Antarctic Research/Scientific Committee on Oceanic Research, 74 pp.

Schofield, O., H.W. Ducklow, D.G. Martinson, M.P. Meredith, M.A. Moline, and W.R. Fraser. 2010. How do polar marine ecosystems respond to rapid climate change? *Science* 328:1,520–1,523, http://dx.doi.org/10.1126/science.1185779.

Smith, W.O. Jr., D.G. Ainley, and R. Cattaneo-Vietti. 2007. Trophic interactions within the Ross Sea continental shelf ecosystem. *Philosophical Transactions of the Royal Society B* 362:95–111, http://dx.doi.org/10.1098/rstb.2006.1956.

Thrush, S., P. Dayton, R. Cattaneo-Vietti, M. Chiantore, V. Cummings, N. Andrew, I. Hawes, S. Kim, R. Kvitek, and A.-M. Schwartz. 2006. Broad-scale factors influencing the biodiversity of coastal benthic communities of the Ross Sea. *Deep Sea Research Part II* 53:959–971, http://dx.doi.org/10.1016/j.dsr2.2006.02.006.

Thrush, S.F., and V.J. Cummings, 2011. Massive icebergs, alteration in primary food resources and changes in benthic communities at Cape Evans, Antarctica. *Marine Ecology* 32:289–299, http://dx.doi.org/10.1111/j.1439-0485.2011.00462.x.

Williams, R.T., and E.S. Robinson. 1980. The ocean tide in the southern Ross Sea. *Journal of Geophysical Research* 85(C11):6,689–6,696, http://dx.doi.org/10.1029/JC085iC11p06689.

Wilson, D.S., S.S.R. Jamieson, P.J. Barrett, G. Leichenkov, K. Gohl, and R.D. Larter. 2012. Antarctic topography at the Eocene-Oligocene boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology* 335–336:24–34, http://dx.doi.org/10.1016/j.palaeo.2011.05.028.

Wilson, D.S., and B.P. Luyendyk. 2006. Bedrock platforms within the Ross Embayment, West Antarctica: Hypotheses for ice sheet history, wave erosion, Cenozoic extension, and thermal subsidence. *Geochemistry Geophysics Geosystems* 7(12), Q12011, http://dx.doi.org/10.1029/2006GC001294.

Wilson, D.S., and B.P. Luyendyk. 2009. West Antarctic paleotopography estimated at the Eocene-Oligocene climate transition. *Geophysical Research Letters* 36, L16302, http://dx.doi.org/10.1029/2009GL039297.