



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Global and Planetary Change 45 (2005) 1–7

GLOBAL AND PLANETARY
CHANGE

www.elsevier.com/locate/gloplacha

Preface

Introduction to ‘long-term changes in Southern high-latitude ice sheets and climate, the Cenozoic history’

1. Introduction

The Cenozoic evolution of the Antarctic cryosphere and fluctuations in its ice sheet cover are considered to be one of the major influences on low- and mid-latitude deep-sea sedimentary records. Long-term Cenozoic trends and short-term climate fluctuations (≤ 40 ka) alike are inferred to have been driven or modulated by changes in Antarctic ice sheet volume (Kennett, 1977; Imbrie and Imbrie, 1980; Zachos et al., 1997, 2001; Shackleton et al., 1999; Lear et al., 2000; Naish et al., 2001). Similarly, changes in sea level elevations at continental margins are also inferred to result from growth and decay in Antarctic ice sheet volume throughout the Cenozoic (Barrett et al., 1987; Haq et al., 1987). Yet, direct records of the Antarctic cryosphere and its ice sheets are sparse at best, and much of the inference remains untested.

Recent efforts have begun to change this, and the last decade has seen several expeditions to the Antarctic and Southern Oceans, which have recovered new high-quality sedimentary core and seismic reflection records of Southern high-latitude Cenozoic ice sheets and climate. These include the Cape Roberts Project (CRP) (Cape Roberts Science Team, 1998; Hambrey et al., 1998; Cape Roberts Science Team, 1999; Barrett et al., 2000; Cape Roberts Science Team, 2000; Barrett et al., 2001; Davey et al., 2001), ODP Leg 177 (Gersonde et al., 1999, 2003), Leg 178 (Barker et al., 1999, 2002), Leg 182

(Feary et al., 2000; Hine et al., 2004), Leg 188 (O’Brien et al., 2001; Cooper et al., 2004), and Leg 189 (Exon et al., 2001, in press), and various RVIB NB Palmer and Polarstern cruises.

Recent results from these expeditions were presented at a special session of the EGS–AGU Joint assembly held in Nice, France, in April 2003. The focus of the session was the many orders and scales of variation of Antarctic ice sheets and climate from Antarctic and sub-Antarctic records derived from outcrop studies, deep sea and continental margin drilling, and seismic reflection investigations. The session also included new modelling results utilizing new data from these recent expeditions and preliminary results of geophysical surveys defining sub-ice shelf and sea ice sedimentary basins identified as drilling targets in the near future under the ANDRILL program (Harwood et al., 2002; Florindo et al., 2003a).

Like the Palaeogeography, Palaeoclimatology, Palaeoecology special issue “Antarctic Cenozoic palaeoenvironments: geologic record and models” (Florindo et al., 2003), this special issue is linked to the Antarctic Climate Evolution (ACE) project, a new Scientific Committee on Antarctic Research (SCAR) initiative to study the climate and glacial history of Antarctica by linking climate and ice sheet modelling studies with geophysical surveys and geological studies on and around the Antarctic continent (Florindo et al., 2003b; <http://www.ace.scar.org/>).

2. Organization and contents

The contributions presented in this special issue of *Global and Planetary Change* represent only a small subset of the scientific results presented at the 2003 EGS–AGU Joint assembly special session, which are included in Volume 5 of the *Geophysical Research Abstracts Journal* (<http://www.copernicus.org/EGU/gra/gra.html>). However, they demonstrate the range of activity and some of the significant recent advances in understanding of Cenozoic evolution and behavior of Southern high-latitude ice sheets and palaeoclimate. The papers represent new geologic information

or new interpretations or compilations of existing data sets from around the Antarctic continent (Fig. 1). Interpretations are based on a range of geological information from seismic reflection surveys to studies of geological drill cores. Two papers also include significant contributions to palaeoclimate modelling of the Antarctica region. The contributions also cover a broad range of Cenozoic time at varying resolutions from the mid-late Eocene to present (Table 1). The volume is organized such that modelling results of the early development of the psychrosphere are presented first (Pollard and DeConto, 2004; Hay et al., 2004) followed by the results of a comparative geomorpho-

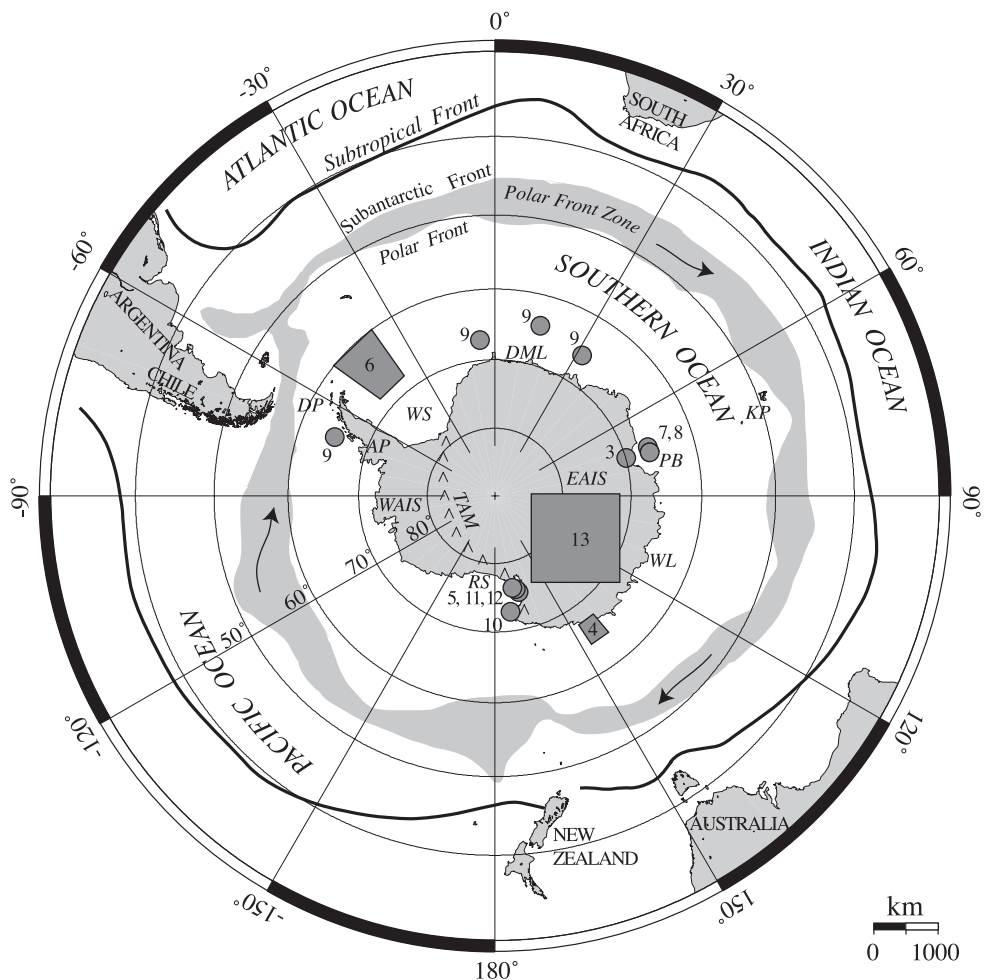


Fig. 1. Polar stereographic projection to 30°S with general locations of areas studied in this issue. Abbreviations of locations: AP, Antarctic Peninsula; DP, Drake Passage; DML, Dronning Maud Land; EAIS, East Antarctic Ice Sheet; KP, Kerguelen Plateau; PB, Prydz Bay; RS, Ross Sea; STR, South Tasman Rise; TAM, Transantarctic Mountains; WAIS, West Antarctic Ice Sheet; WL, Wilkes Land; WS, Weddell Sea.

speculative look at the mechanism for the major isotopic excursion at the Eocene–Oligocene boundary. Many workers now contend that this excursion resulted from continent-wide glaciation of Antarctica, and they justify the ice volume explanation above temperature because, if the isotopic excursion were due solely to temperature, it would require freezing of the ocean to a significant depth (Kennett, 1977; Flower, 1999). Hay et al. (2004), however, contend that higher salinity oceans in the Palaeogene would lower the freezing point to the degree that such a claim no longer holds and only a secondary part of the $\delta^{18}\text{O}$ change is related to the formation of permanent sea ice on the Arctic and perhaps in areas around Antarctica. Their observations of modelling and ocean drilling data point to early formation of the psychrosphere at the Eocene–Oligocene boundary, coincident with the development of the modern oceanic structure, but they contend that continent-wide glaciation may not have been fully developed until the middle Oligocene.

The third modelling paper presented in the volume (Jamieson et al., 2004) evaluates the relative influence of fluvial vs. glacial processes pre- and postdevelopment of the psychrosphere. In the model, previously eroded sediment is back-stacked onto the Antarctic craton using a sediment volume estimated from ODP drilling in Prydz Bay. The paper identifies that a preglacial fluvial topography survives beneath the Lambert graben and that this preexisting topography has been the principal forcing factor on subsequent erosion. An interesting discovery is the model prediction of the existence of a large preglacial lake in the cratonic interior of Antarctica. While somewhat speculative, the validity of the findings is qualified by a sensitivity test on the volumes of sediment back-stacked by the model.

The first of the papers discussing evidence for Cenozoic Antarctic glaciation from the Antarctic margin is from Escutia et al. (2004) and outlines the nature of glacial stratigraphy, sedimentation, and processes in the Wilkes Land margin of Antarctica. In addition, it provides inferences about the nature and timing of Cenozoic glacial events from the onset of glaciation in this margin to the Holocene. The authors outline a strategy for deep sampling (i.e., IODP-type techniques) that would ground truth their inferences on the long-term record of multiple growth and collapse of the EAIS and related sea level, palae-

oceanographic, and palaeoenvironmental changes from the Wilkes Land margin. An IODP proposal (482) is currently under review (see details at www.isas-office.jp/active_pdf/482-Full3_Escuti.pdf).

Horgan et al. (2004) present new multichannel seismic reflection data collected from the McMurdo–Ross Ice Shelf, Antarctica. The authors, from the analysis of seismic geometry, stratal terminations, and the interpretation of seismic facies, develop a stratigraphic architecture for the moat-fill succession and speculate on the timing of development of accommodation in response to the evolution of the Ross Island volcanic complex. The moat region has accommodated a well-stratified regionally extensive sedimentary succession in the deepest part of the depression, providing a unique opportunity to recover highly sensitive and complete record of the dynamics and variability of the West Antarctic Ice Sheet and McMurdo–Ross Ice Shelf in western Ross Sea. This stratigraphic record is scheduled to be drilled by the ANDRILL Programme in the austral summer of 2006 (see details at <http://andrift-server.unl.edu/>).

The contribution by Maldonado et al. (2004) reports on multichannel and high-resolution seismic profiles complemented by swath bathymetry showing an extensive field of contourite deposits in the northern Weddell Sea. From these data, they draw inferences about the influence of the Weddell Sea Bottom Water flows on sea-bottom processes and related depositional patterns in the northern Weddell Sea and define its palaeoceanographic evolution since the early Miocene.

In the first contribution presenting new results from drilling and coring studies of the Antarctic margin, Grützner et al. (2004) report on the sediment record recovered during ODP Leg 188 at Site 1165 (Prydz Bay), focusing on the late Miocene–early Pliocene time interval, and compare these findings with the results from ODP Site 1095 (Antarctic Peninsula) and 1088 (Agulhas Ridge, Southern Ocean). Using biogenic opal depositional rates, they report evidences of an early Pliocene reduction in sea ice at Sites 1165 and 1095 that is in agreement with a warm period, as documented from other proxies in the Southern Ocean (e.g., Hillenbrand and Ehrmann, 2004). East and West Antarctic ice sheet growth at about 7 and 5 Ma is inferred from enhanced mass accumulation rates of terrigenous-derived particles.

Ocean Drilling Program Site 1165 is also the focus of the next paper (Junttila et al., 2004). Aiming to show the possible intervals of expansions of the ice sheet across the continental shelf off Prydz Bay and possible expression of the “middle” Pliocene warm period, the authors report a detailed clay minerals study of the uppermost sediment column between 0 and 50 mbsf, which consists of a section of hemipelagic and pelagic Pliocene–Pleistocene sediments. These results, integrated with oxygen isotopes and magnetic properties determinations, indicate a general long-term cooling trend from 5 Ma to the present, with evidences of a general warming trend towards 3.2 Ma.

The contribution by Hillenbrand and Ehrmann (2004) provides late Neogene records of clay mineralogy and biogenic opal for the Antarctic Peninsula (ODP Leg 178 and Sites 1095 and 1096). Short-term clay mineralogical fluctuations in the ODP cores indicate that repeated ice advances and retreats in response to a varying size of the Antarctic Peninsula ice cap are likely to have occurred throughout the late Neogene and Quaternary. In addition, by comparing the Pliocene–Pleistocene opal record from the Bellingshausen Sea with corresponding records from the Atlantic and Indian sector of the Southern Ocean (RV Polarstern cores), the authors point out that the opal record on the Pacific margin of the Antarctic Peninsula is also representative for the East Antarctic continental margin.

The contribution by Finocchiaro et al. (2004) presents new results from an interesting core that records palaeoenvironmental conditions through the transition from glacial to interglacial conditions of the Holocene. Important changes in diatom production and seasonal laminations document the state of the water column and the influx of sediments from the surrounding mountains. This high level of resolution enables the authors to discuss processes associated with the sediment record and thus obtain greater information on the nature of Antarctic palaeoenvironmental change. The results mirror data from other regions of Antarctica.

Recently, a series of three holes was drilled in McMurdo Sound, Ross Sea as part of the Cape Roberts Project (CRP) (Cape Roberts Science Team, 1998, 1999, 2000; Hambrey et al., 1998; Barrett et al., 2000, 2001). This project was a cooperative venture

between scientists from seven countries, i.e., Australia, Britain, Germany, Italy, The Netherlands, New Zealand, and the USA, and it was set-up to investigate the early history of the EAIS and the West Antarctic Rift System by coring approximately 1500 m of Cenozoic strata and 100 m of Palaeozoic-age Beacon Supergroup rocks at the edge of the present ice sheet and close to the TAM.

Florindo et al. (2004) synthesize the results of palaeomagnetic analyses carried out on the CRP-1, CRP-2, and CRP-3 sediment cores and present an integrated chronology for the Eocene–Miocene succession (1472-m cumulative record). These results permit comparison with lower latitude records and allow rates and modes of sedimentation to be established for the western margin of the Victoria Land Basin in close proximity to the Transantarctic Mountains and East Antarctic craton.

Bellanca et al. (2004) provide the first record at adequate resolution of bulk carbonate isotope compositions and carbonate petrography from upper Eocene and lower Oligocene siliciclastic sediments of the CRP-3 sediment core. The $\delta^{18}\text{O}$ record exhibits a number of steps in an upward increasing trend that are thought to reflect the evolution of ice sheet growth over the late Eocene to early Oligocene in response to a global cooling trend. Low carbonate $\delta^{13}\text{C}$ values suggest that organic reactions have played a significant role in modifying the pore fluid chemistry. Some anomalously light carbon compositions are interpreted as a record of methane-derived CO_2 addition to the system.

The last contribution dealing with palaeoclimate modelling of the Antarctica region is presented by Siebert et al. (2004). The authors detail the subglacial roughness across East Antarctica from the spectral analysis of radio-echo sounding data. Roughness calculations are compared with numerical ice sheet modelling results to establish relationships between modern ice sheet dynamics and the roughness of its bed. Of particular interest, the authors try to identify whether the roughness of subglacial East Antarctica is consistent with an unchanging or changeable ice mass.

Acknowledgements

The stimulus that led to the conception of this special issue of Global and Planetary Change was the

EGS–AGU Joint assembly that was held in Nice, France, in April 2003. We gratefully acknowledge all the reviewers for their valuable criticism, comments, and suggestions that substantially improved the quality of the manuscripts. We acknowledge their very special contributions to this special issue by naming them here: A. Abe-Ouchi, P.J. Barrett, S.M. Bohaty, S.A. Brachfeld, S. Cande, C. Clark, A. Cooper, R.M. DeConto, E. Domack, C.R. Fielding, C.F. Forsberg, M.J. Hambrey, J.A. Howe, G. Leitchenkov, A. Leventer, R.A. Livermore, A. Negri, P.E. O'Brien, B. Oglesby, S. Passchier, S. Pekar, R.D. Powell, C.J. Pudsey, M. Rebesco, T. Stern, G. Villa, D.A. Warnke, J. Whitehead, and S.W. Wise.

Finally, we thank Femke Wallien and Tonny Smit of Elsevier Science and our Editor-in-Chief Sierd Cloetingh who provided valuable advice and supported the production of this special issue. The special issue would not have become reality without them.

References

- Barker, P.F., Camerlenghi, A., Acton, G.D., et al., 1999. Proc. ODP, Init. Repts., 178 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/178_IR/178TOC.HTM.
- Barker, P.F., Camerlenghi, A., Acton, G.D., Ramsay, A.T.S. (Eds.), 2000. Proc. ODP, Sci. Results 178 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/178_SR/178sr.htm.
- Barrett, P.J., Elston, D.P., Harwood, D.M., McKelvey, B.C., Webb, P.-N., 1987. Mid-Cenozoic record of glaciation and sea-level change on the margin of the Victoria Land Basin, Antarctica. *Geology* 15, 634–637.
- Barrett, P.J., et al., (Eds.), 2000. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Scientific results of CRP-2/2A: Parts I and II. *Terra Antarctica*, vol. 7, pp. 1–665.
- Barrett, P.J., et al., (Eds.), 2001. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Scientific results of CRP-3: Parts I and II. *Terra Antarctica*, vol. 8, pp. 1–621.
- Bellanca, A., Aghib, F., Neri, R., Sabatino, N., 2005. Bulk carbonate isotope stratigraphy from CRP-3 core (Victoria Land Basin, Antarctica): evidence for Eocene–Oligocene palaeoclimatic evolution. *Glob. Planet. Change* 45, 227–237 (*this issue*).
- Cape Roberts Science Team, 1998. Initial Report on CRP-1, Cape Roberts Project, Antarctica. *Terra Antarctica* 5, 1–187.
- Cape Roberts Science Team, 1999. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Initial Report on CRP-2/2A. *Terra Antarctica* 6, 1–173 (with supplement, 245 pp.).
- Cape Roberts Science Team, 2000. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Initial Report on CRP-3. *Terra Antarctica* 7, 1–209 (with supplement, 305 pp.).
- Cooper, A.K., O'Brien, P.E., Richter, C. (Eds.), 2004. Proc. ODP, Sci. Results, 188 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/188_SR/188sr.htm.
- Davey, F.J., Barrett, P.J., Cita, M.B., van der Meer, J.J.M., Tessensohn, F., Thomson, M., Webb, P.-N., Woolfe, K.J., 2001. Drilling for Antarctic Cenozoic climate and tectonic history at Cape Roberts, southwestern Ross Sea. *EOS Trans.-Am. Geophys. Union* 82 (48), 585.
- Escutia, C., De Santis, L., Donda, F., Dunbar, R.B., Cooper, A.K., Brancolini, G., Eittrheim, S.L., 2005. Cenozoic ice sheet history from East Antarctic Wilkes Land continental margin sediments. *Glob. Planet. Change* 45, 51–81 (*this issue*).
- Exon, N.F., Kennett, J.P., Malone, M.J., et al., 2001. Proc. ODP, Init. Repts., 189 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/189_IR/189ir.htm.
- Exon, N.F., Kennett, J.P., Malone, M.J. (Eds.), in press. Proc. ODP, Sci. Results, 189 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/189_SR/189sr.htm.
- Feary, D.A., Hine, A.C., Malone, M.J., et al., 2000. Proc. ODP, Init. Repts., 182 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/182_IR/182ir.htm.
- Finocchiaro, F., Langone, L., Colizza, E., Fontolan, G., Giglio, F., Tuzzi, E., 2005. Record of the early Holocene warming in a laminated sediment core from Cape Hallett Bay (northern Victoria Land, Antarctica). *Glob. Planet. Change* 45, 191–204 (*this issue*).
- Florindo, F., Cooper, A.K., O'Brien, P.E. (Eds.), 2003. Antarctic Cenozoic palaeoenvironments: geologic record and models, Palaeogeography, Palaeoclimatology, Palaeoecology, 198, 1–278.
- Florindo, F., Francis, J., Harwood, D.M., Levy, R.H., Naish, T., Niessen, F., Powell, R.D., Wilson, G.S., 2003a. The ANDRILL initiative: stratigraphic drilling for climatic and tectonic history in Antarctica. *Terra Antarctica Report* 9, 123–126.
- Florindo, F., Dunbar, R.B., Siebert, M.J., Deconto, R.M., Barrett, P.J., Cooper, A.K., Escutia, C., Janecek, T.R., Larter, R.D., Naish, T.R., Powell, R.D., 2003b. Antarctic climate evolution (ACE) research initiative. *Terra Antarctica Report* 9, 127–132.
- Florindo, F., Wilson, G.S., Roberts, A.P., Sagnotti, L., Verosub, K.L., 2005. Magnetostratigraphic chronology of a late Eocene to early Miocene glacial marine succession from the Victoria Land Basin, Ross Sea, Antarctica. *Glob. Planet. Change* 45, 205–226 (*this issue*).
- Flower, B.P., 1999. Cenozoic deep-sea temperatures and polar glaciation: the oxygen isotope record. *Terra Antarctica Report* 3, 27–43.
- Gersonde, R., Hodell, D.A., Blum, P., et al., 1999. Proc. ODP, Init. Repts., 177 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/177_IR/177TOC.HTM.
- Gersonde, R., Hodell, D.A., Blum, P. (Eds.), 2003. Proc. ODP, Sci. Results, 177 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/177_SR/177sr.htm.

- Grützner, J., Hillenbrand, C., Rebesco, M., 2005. Terrigenous flux and biogenic silica deposition at the Antarctic continental rise during the late Miocene to early Pliocene: implications for ice sheet stability and sea ice coverage. *Glob. Planet. Change* 45, 129–147 ([this issue](#)).
- Hambrey, M.J., et al., (Eds.), 1998. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Scientific results of CRP-1. Terra Antarctica, vol. 5, pp. 255–713.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science* 235, 1156–1167.
- Harwood, D.M., Lacy, L., Levy, R.H. (Eds.), 2002. Antarctic margin drilling: developing a science program plan for McMurdo sound. ANDRILL SMO Contribution 1, University of Nebraska-Lincoln, NE. 301 pp.
- Hay, W.W., Flögel, S., Söding, E., 2005. Is the initiation of glaciation on Antarctica relate to a change in the structure of the ocean? *Glob. Planet. Change* 45, 23–33 ([this issue](#)).
- Hillenbrand, C., Ehrmann, W., 2005. Late Neogene to Quaternary environmental changes in the Antarctic Peninsula region: evidence from drift sediments. *Glob. Planet. Change* 45, 163–189 ([this issue](#)).
- Hine, A.C., Feary, D.A., Malone, M.J. (Eds.), 2004. Proc. ODP, Sci. Results, p. 182 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/182_SR/182sr.htm.
- Horgan, H., Naish, T., Bannister, S., Balfour, N., Wilson, G., 2005. Seismic stratigraphy of the Plio–Pleistocene Ross Island flexural moat-fill: a prognosis for ANDRILL program drilling beneath McMurdo–Ross Ice Shelf. *Glob. Planet. Change* 45, 83–97 ([this issue](#)).
- Imbrie, J., Imbrie, J.Z., 1980. Modeling the climatic response to orbital variations. *Science* 207, 943–953.
- Jamieson, S.S.R., Hulton, N.R.J., Sugden, D.E., Payne, A.J., Taylor, J., 2005. Cenozoic landscape evolution of the Lambert basin, East Antarctica: the relative role of rivers and ice sheets. *Glob. Planet. Change* 45, 35–49 ([this issue](#)).
- Junttila, J., Ruikka, M., Strand, K., 2005. Clay mineral assemblages in high-resolution Plio–Pleistocene interval at ODP site 1165, Prydz Bay, Antarctica. *Glob. Planet. Change* 45, 149–161 ([this issue](#)).
- Kennett, J.P., 1977. Cenozoic evolution of Antarctic glaciation, the circum-Antarctic ocean, and their impact on global oceanography. *J. Geophys. Res.* 82, 3843–3859.
- Lear, C.H., Elderfield, H., Wilson, P.A., 2000. Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite. *Science* 287, 269–272.
- Maldonado, A., Barnolas, A., Bohoyo, F., Escutia, C., Galindo-Zaldívar, J., Hernández-Molina, J., Jabaloy, A., Lobo, F.J., Nelson, C.H., Rodríguez-Fernández, J., Somoza, L., Vázquez, J.T., 2005. Miocene to recent contourite drifts development in the northern Weddell Sea (Antarctica). *Glob. Planet. Change* 45, 99–128 ([this issue](#)).
- Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S., Atkins, C., Bohaty, S.M., Buckler, C.J., Claps, M., Davey, F.J., Dunbar, G.B., Dunn, A.G., Fielding, C.R., Florindo, F., Hannah, M.J., Harwood, D.M., Henrys, S.A., Krissek, L.A., Lavelle, M., Meer, J., McIntosh, W.C., Niessen, F., Passchier, S., Powell, R.D., Roberts, A.P., Sagnotti, L., Scherer, R.P., Strong, C.P., Talarico, F., Verosub, K.L., Villa, G., Watkins, D.K., Webb, P.-N., Wonik, T., 2001. Orbitally induced oscillations in the east Antarctic ice sheet at the Oligocene/Miocene boundary. *Nature* 413, 719–723.
- O’Brien, P.E., Cooper, A.K., Richter, C., et al., 2001. Proc. ODP, Init. Repts., 188 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/188_IR/188ir.htm.
- Pollard, D., DeConto, R.M., 2005. Hysteresis in cenozoic Antarctic ice sheet variations. *Glob. Planet. Change* 45, 9–21 ([this issue](#)).
- Shackleton, N.J., Crowhurst, S.J., Weedon, G.P., Laskar, J., 1999. Astronomical calibration of Oligocene–Miocene time. *Philos. Trans. R. Soc.* 357 (1757), 1907–1929.
- Siegert, M.J., Taylor, J., Payne, A.J., 2005. Spectral roughness of subglacial topography and implications for former ice-sheet dynamics in East Antarctica. *Glob. Planet. Change* 45, 239–253 ([this issue](#)).
- Zachos, J.C., Flower, B.P., Paul, H., 1997. Orbitally paced climate oscillations across the Oligocene/Miocene boundary. *Nature* 388, 274–278.
- Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to Present. *Science* 292, 686–693.

Fabio Florindo*

*Istituto Nazionale di Geofisica e Vulcanologia,
Via di Vigna Murata 605, 00143 Rome, Italy
E-mail address: florindo@ingv.it.*

*Corresponding author. Tel.: +39 06 5186 0383;
fax: +39 06 5186 0397.

David M. Harwood

*Department of Geosciences,
University of Nebraska-Lincoln,
Lincoln, NE 68588-0340, USA*

Gary S. Wilson

*Department of Geology, University of Otago,
P.O. Box 56, Dunedin, New Zealand*