East Antarctic Ice Sheet fluctuations during the Middle Miocene Climatic Transition inferred from faunal and biogeochemical data on planktonic foraminifera (ODP Hole 747A, Kerguelen Plateau)

M. Verducci,[1] L. M. Foresi,[1] G. H. Scott,[2] M. Tiepolo,[3] M. Sprovieri,[4] and F. Lirer[4]

[1]Department of Earth Sciences, University of Siena, Via Laterina 8, 53100 Siena, Italy (verducci@unisi.it; foresi@unisi.it)
[2]GNS Science, 1 Fairway Drive, Avalon, PO Box 30 368, Lower Hutt, New Zealand (g.scott@gns.cri.nz)
[3]Istituto di Geoscienze e Georisorse, C.N.R., Via Ferrata 1, 27100 Pavia, Italy (tiepolo@crystal.unipv.it)
[4]Istituto per l'Ambiente Marino Costiero, C.N.R., Calata Porta di Massa, 80100 Napoli, Italy (mario.sprovieri@iamc.cnr.it; fabrizio.lirer@iamc.cnr.it)

Abstract This research focuses on a detailed study of faunal and biogeochemical changes that occurred at ODP Hole 747A in the Kerguelen Plateau region of the Southern Ocean during the middle Miocene (14.8-11.8 Ma). Abundance fluctuations of several planktonic foraminiferal taxa, stable oxygen isotope and Mg/Ca ratios have been integrated as a multi-proxy approach to reach a better understanding of the growth modality and fluctuations of the East Antarctic Ice Sheet (EAIS) during this period. A 7°C decrease in Sea Surface Temperature (SST), an abrupt turnover in the planktonic foraminiferal assemblage, a 1.5‰ shift towards heavier $\delta^{18}O$ values (Mi3 event) and a related shift towards heavier seawater $\delta^{18}O$ values between 13.9 and 13.7 Ma, are interpreted to reflect rapid surface water cooling and EAIS expansion. Hole 747A data suggest a major change in the variability of the climate system fostered by EAIS expansion between 13.9 and 13.7 Ma. Ice sheet fluctuations were greater during the interval 14.8-13.9 Ma compared with those from 13.7 to 11.8 Ma, whereas the latter interval was characterized by a more stable EAIS. In our opinion, the middle Miocene ice sheet expansion in Antarctica represents a first step towards the development of the modern permanent ice sheet.

Citation: Verducci, M., L. M. Foresi, G. H. Scott, M. Tiepolo, M. Sprovieri and F. Lirer (2007), East Antarctic Ice Sheet fluctuations during the Middle Miocene Climatic Transition inferred from faunal and biogeochemical data on planktonic foraminifera (Kerguelen Plateau), in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A. K. Cooper and C. R. Raymond et al., USGS Open-File Report 2007-1047, Short Research Paper 037, 5 p.; doi:10.3133/of2007-1047.srp037

Introduction

Antarctic ice sheets and Southern Ocean waters are major components of Earth's climate system, strongly influencing global ocean and atmospheric circulation. The long-term evolution of the Antarctic cryosphere is currently under much debate, since it is not yet clear when the East Antarctic Ice Sheet (EAIS) changed its character from polythermal or "wet based" to stable or "dry based" (Kennett and Hodell, 1995; Harwood and Webb, 1998; Stroeven et al., 1998; Hambrey and McKelvey, 2000; Grützner et al., 2003). Better understanding of the Cenozoic history of the Antarctic cryosphere, in particular, its behavior during periods of great climatic instability and its relation to global climate, is necessary to address this topic.

The middle Miocene represents a major step in Cenozoic climatic evolution. After the Miocene Climatic Optimum (MCO; 17-15 Ma) a stepwise cooling (Middle Miocene Shift, MMS; from 14.2 to 13.8 Ma, according to Shevenell et al. [2004] and Holbourn et al. [2005]) occurred at middle and high latitudes and culminated in the late Miocene (Flower and Kennett, 1994). In order to analyze the features of the Middle Miocene Climatic Transition (MMCT) and to better outline the history of the EAIS, a high-resolution study of integrated stratigraphy, based on micropaleontological (qualitative and quantitative analyses of planktonic foraminiferal assemblages) and biogeochemical tools (Mg/Ca ratio and $\delta^{18}O$ analysis), was carried out on sediments from ODP Site 747, Hole A (Kerguelen Plateau, Indian Ocean sector of the Southern Ocean).

For the first time a biogeochemical record (Mg/Ca and $\delta^{18}O$) has been compared with a micropaleontological quantitative study to infer the timing and history of Antarctic Cryosphere evolution and to better outline the global climatic change.

Materials and methods

Hole 747A samples have been analyzed at 8 cm spacing (~16 k.y. temporal resolution). Quantitative analyses of planktonic foraminiferal assemblages were performed on the >125 μm fraction and provided information about abundance fluctuations of taxa with different climatic affinities (cold, temperate and "warm" indices). $\delta^{18}O$ and Mg/Ca analyses were performed on *Globigerina praebulloides* tests, a taxon that is closely related to the extant species *Globigerina bulloides*, and with similar environmental preferences. Mg/Ca ratios were measured through *in-situ* determination of Mg and Ca content in foraminiferal tests by Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP MS) (Reichart et al., 2003; Eggins et al., 2003).

The age model for Hole 747A (Fig. 1) is based on the magnetostratigraphy of Heider et al. (1992), compared with the stable isotope results of Wright and Miller (1992), and correlated to the ATNTS2004 (Astronomically Tuned Neogene Time Scale 2004) of Lourens et al. (2004).

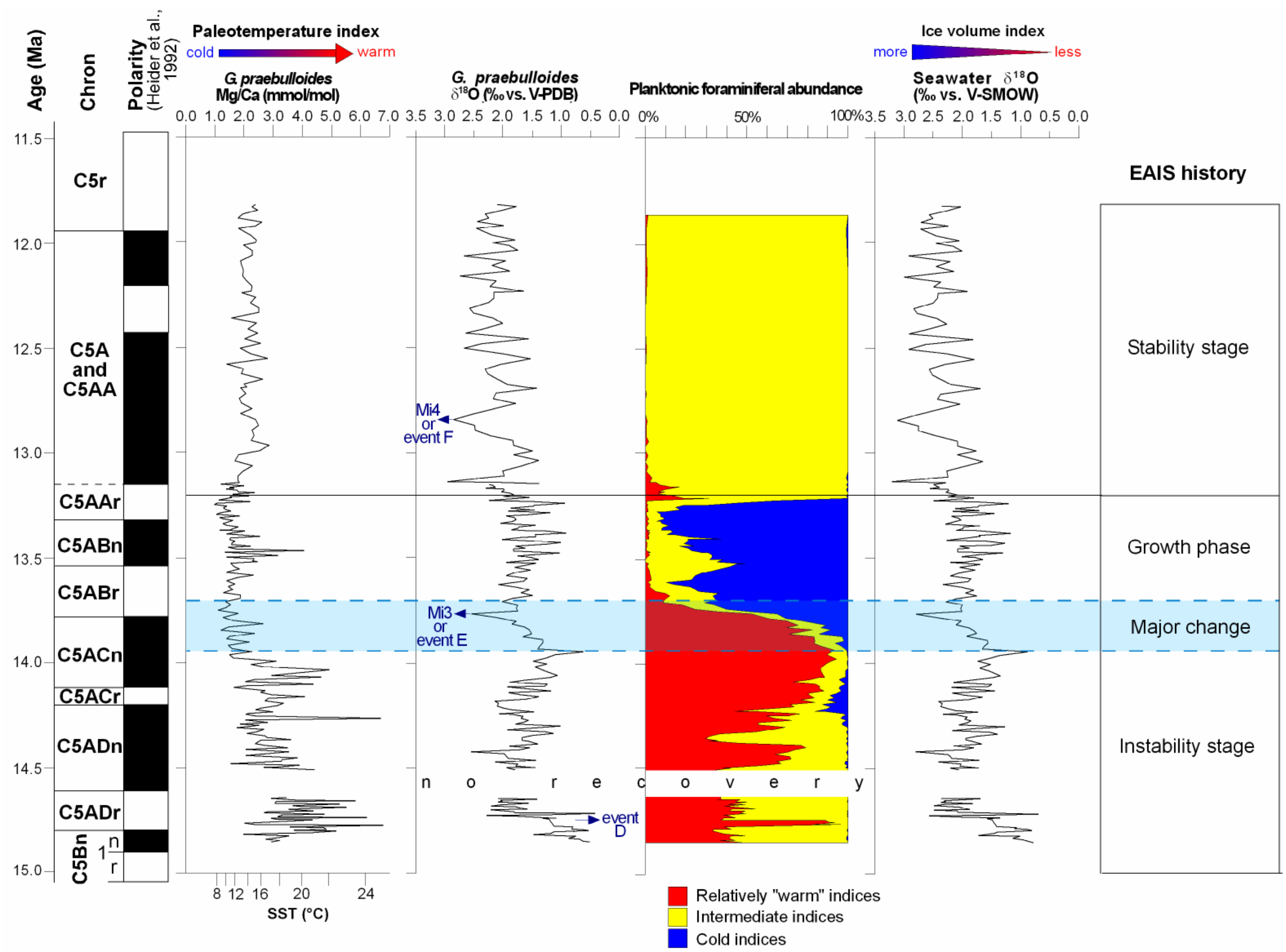

Figure 1. Comparison of Hole 747A micropaleontological and biogeochemical data plotted against age (Ma). The age model (on the left) is based on Hole 747A magnetic polarity of Heider et al. (1992), interpreted through the isotope stratigraphy events recognized by Wright and Miller (1992), and correlated to the ATNTS 2004 of Lourens et al. (2004). Oxygen stable isotope and Mg/Ca analyses (on the left) were performed on *Globigerina praebulloides* tests. Mg/Ca data were converted to paleotemperature data (Sea Surface Temperature expressed in °C) using the Mg/Ca-temperature calibration equation of Mashiotta et al. (1999). The main oxygen isotope events (according to Miller et al., 1991 and Woodruff and Savin, 1991) are shown. Planktonic foraminiferal taxa have been grouped on the basis of their ecological affinities (relatively "warm", temperate and cold indices). The abundance fluctuations of those three groups are shown. On the right, seawater $\delta^{18}O$ fluctuations are shown. Seawater $\delta^{18}O$ has been calculated from Mg/Ca-derived paleotemperature data and calcite $\delta^{18}O$ data using the Shackleton (1974) equation. A record of changes in surface seawater $\delta^{18}O$ provides valuable information about the timing of growth and decay of continental ice sheets because it represents the ice volume signal. On the right, the history of the EAIS during the Middle Miocene Climatic Transition is shown.

Results

Biofacies results

The different abundance patterns of planktonic foraminifers allowed the recognition of three main biofacies in the middle Miocene sequence of Hole 747A (Fig. 1).

Biofacies 1 (14.8-13.7 Ma). Spans the lower part of studied sequence and is mainly characterized by *Globorotalia miozea* group and *Globoturborotalita woodi* group taxa, which comprise 80-90% of the total planktonic foraminiferal assemblage. These taxa are relatively "warm" water forms, which preferred temperate to warm subtropical environments.

Biofacies 2 (13.7-13.2 Ma). Spans the middle part of the studied sequence and is distinguished from Biofacies 1 on the basis of the almost total disappearance of Biofacies 1 taxa and their replacement by globigerinids and especially neogloboquadrinids. The Biofacies 2 fauna is nearly monospecific, since it is dominated by *Neogloboquadrina nympha*, which constitutes up to 90% of the assemblage. *Neogloboquadrina nympha* is phyletically related to the extant species *Neogloboquadrina pachyderma* (sinistral), and its high abundance suggests that like its modern counterpart it was a dominator of cold polar environments.

Biofacies 3 (13.2-11.8 Ma). Spans the upper part of the studied sequence and is distinguished from Biofacies 2 on the basis of an abrupt decrease in the abundance of neogloboquadrinids, and a corresponding rapid increase in species with temperate affinities (*Globorotalia praescitula*, *Globigerina falconensis*, *Globigerinita glutinata*, *Tenuitellinata uvula* and paragloborotalids).

The taxa that dominate Biofacies 1 are extremely rare in Biofacies 2, and they are completely absent from Biofacies 3. Neogloboquadrinids are only dominant in Biofacies 2, and paragloborotalids are restricted to Biofacies 3.

Planktonic foraminiferal Mg/Ca and paleotemperature reconstruction

Mg/Ca ratios measured on foraminiferal tests are a rapidly emerging tool for reconstructing paleo-seawater temperature (Pahnke et al., 2003; Shevenell et al., 2004). Mg incorporation into calcitic tests secreted by foraminifers is extraordinarily sensitive to the calcification temperature. The Mg/Ca ratio in foraminiferal tests increases exponentially with temperature (Rosenthal et al., 1997) and, unlike δ^{18}O, is relatively insensitive to salinity and ice-volume fluctuations (Lea et al., 1999).

LA-ICP MS analysis performed on *G. praebulloides* tests enabled the construction of a paleo-Sea Surface Temperature (paleo-SST) curve for the middle Miocene at Site 747 (Fig. 1), using the Mg/Ca-temperature calibration equation of Mashiotta et al. (1999).

The highest SSTs (Fig. 1) are recorded from 14.8 to 14.0 Ma, probably representing the termination of the MCO. This is followed by an abrupt decrease (ca. 7°C) in SST at about 13.9 Ma, leading to an extended period of low temperatures (ca. 10°C). After 13.2 Ma, SSTs warm slightly and remain relatively stable at about 14°C thereafter.

Planktonic foraminiferal δ^{18}O

The lightest *Globigerina praebulloides* δ^{18}O values occur between 14.8 and 14.7 Ma (Fig. 1), and might correspond to event D of Woodruff and Savin (1991). From this point upwards δ^{18}O values tend to increase. A very significant shift (1.5‰) towards heavier values is recorded at 13.9-13.7 Ma and corresponds to the Mi3 event (Miller et al., 1991) or event E of Woodruff and Savin (1991). A second shift (ca. 1‰) follows at 12.8 Ma and represents the Mi4 event (Miller et al., 1991) or event F (Woodruff and Savin, 1991). Shorter term fluctuations are superimposed on the overall increasing trend.

Seawater δ^{18}O

Mg/Ca-derived SST and foraminiferal δ^{18}O can be used together to directly assess changes in seawater δ^{18}O composition (Mashiotta et al., 1999). Foraminiferal δ^{18}O reflects both the temperature and the isotopic composition of seawater in which the foraminiferal test was secreted. Seawater δ^{18}O varies as a function of changes in global ice volume and regional hydrological changes. Because both climatic cooling (temperature-dependent fractionation) and ice sheet growth associated with glacial episodes result in more positive δ^{18}O, it is difficult to isolate the magnitude of each effect. The relative influences on the calcite δ^{18}O record can be derived by combining Mg/Ca-based SST estimates with measured planktonic foraminiferal δ^{18}O and by using an oxygen isotope-paleotemperature equation to compute the change in seawater δ^{18}O. A record of changes in surface seawater δ^{18}O provides valuable information about the timing of growth and decay of continental ice sheets. In this study planktonic foraminiferal Mg/Ca and δ^{18}O data have been used to calculate seawater δ^{18}O using the Shackleton (1974) equation.

The overall trend of seawater δ^{18}O (Fig. 1) closely mimics that of planktonic foraminiferal δ^{18}O. After a period of very light values (14.8-14.7 Ma), a significant increase commences at 13.9 Ma, and reaches a relative maximum at 13.7 Ma. δ^{18}O values then increase again to reach the heaviest values for any part of the studied sequence at about 12.7 Ma. After that, the δ^{18}O values remain relatively stable (ca. 2.5‰).

Discussion

The long-term evolution of the Antarctic cryosphere is currently under much debate, partly because of the hypothesis of Webb and Harwood (1991) and Barrett et al. (1992) that Antarctic ice sheets were very unstable during the late Neogene. A major growth phase of the EAIS characterized the middle Miocene from 16 to 12 Ma (Flower and Kennett, 1994, and references therein), linked to a main permanent step in Cenozoic cooling that occurred in the middle Miocene. This event was associated with increased production of cold Antarctic deep waters and major growth of the EAIS, thus it represents an important step between the initiation of global cooling following the early middle Eocene and the establishment of the modern ocean-climate system.

Planktonic foraminiferal abundance, paleo-SST, planktonic foraminiferal δ^{18}O, and seawater δ^{18}O records from Hole 747A identify a significant change in variability of the climate system at ~13.9-13.7 Ma (Fig. 1). After a relatively warm interval (14.8-13.9 Ma; probably corresponding to the latter part of the MCO), SSTs decrease by 7°C, there is a major turnover in planktonic foraminiferal fauna, characterized by an abrupt influx of neogloboquadrinids (probably corresponding to a migration northward of the Polar Front), there is also a 1.5‰ shift in δ^{18}O towards heavier values (Mi3 event) and seawater δ^{18}O values reflect a major ice growth phase. These changes represent a pivotal threshold in ocean-climate history and in the development of the EAIS. Decreased variability in oxygen isotope (both planktonic foraminiferal and seawater) and paleo-SST records after ~13.9-13.7 Ma, relative to the previous interval, suggests Antarctic cryospheric development resulted in increased stability of the EAIS. To the extent that large-scale variations in the δ^{18}O signal before 13.7 Ma mainly reflect ice volume, ice sheet fluctuations must have been greater during the interval 14.8-13.9 Ma compared with that from 13.7 to 11.8 Ma, taking into account the greater magnitude of variation in $\delta^{18}O$ during the former period. Biogeochemical and micropaleontological records from Hole 747A show a three step evolution (Fig. 1) of the EAIS: 1) The Antarctic cryosphere was unstable during the early middle Miocene, prior to a major EAIS growth phase at 13.9-13.7 Ma (Mi3 event); 2) The major ice volume increase occurred at 13.7 Ma; 3) From our data we speculate that East Antarctic major ice growth may have resulted in a more stable EAIS (from 13.2 Ma) and a corresponding decrease in variability of the climate system. We think that the EAIS changed from a "temperate" or "polythermal" state typical of a wet-based ice sheet to the "polar" state of a dry-based permanent ice sheet. These results are consistent with other evidence for the Antarctic cryosphere expansion reported by Zachos et al. (2001), Shevenell et al. (2004), and Holbourn et al. (2005). Therefore, the warming beginning at 13.2 Ma, as demonstrated by the neogloboquadrinid decrease and the dominance of temperate water taxa, does not appear to have had a major influence on EAIS variability, since the SST increase was accompanied by a continuous decrease in seawater $\delta^{18}O$ at Hole 747A, accounting for further ice volume increase in East Antarctica. The SST increase did not reach the threshold level necessary for significant ice melting.

In conclusion, from 13.9 Ma a significant cryosphere expansion occurred in Antarctica (Shevenell et al., 2004; Holbourn et al., 2005; this study). In our opinion, it led to the development of a semi-permanent ice sheet. Shevenell and Kennett (2004) suggested that the middle Miocene event of Antarctic ice sheet expansion led to an ice volume equivalent to 85% of present; a prelude to the development of the present permanent Antarctic ice sheet.

Growth of the EAIS up to its present day size has involved a number of threshold events and feedback mechanisms, which are linked to further global cooling related to the development of the West Antarctic Ice Sheet (WAIS) in the late Miocene and of the Northern Hemisphere Ice Sheets (NHIS) in the Plio-Pleistocene. In our opinion, the development of the WAIS and the NHIS resulted in a large-scale reorganization of the ocean-climate system, driven by tectonic reconfiguration of gateway regions and/or changes in atmospheric conditions which may have altered meridional heat and moisture transport, resulting in further growth of ice on the Antarctic continent and in the evolution of the EAIS into its present permanent character.

Conclusion

The major cooling of the middle Miocene occurred between 13.9 and 13.7 Ma and caused significant ice volume increase in East Antarctica. The cryosphere expansion led to the stabilization of the EAIS and, as a consequence, to the reduction in variability of the climate system. It represents the first step towards a permanent and stable (dry-based) EAIS as it is today. In this respect, the Middle Miocene Climatic Transition represents a pivotal step in the development of the modern climatic and cryospheric system.

Acknowledgements. These results represent a part of an ongoing research project funded by the Italian program for Antarctic research (PNRA). This research used samples provided by the Ocean Drilling Program (ODP). We would like to thank Prof. Carlo Alberto Ricci for helpful discussion of data and useful comments and suggestions which greatly improved the manuscript.

References

Barrett, P. J., C. J. Adams, W. C. McIntosh, C. C. Swisher III and G. S. Wilson (1992), Geochronological evidence supporting Antarctic deglaciation three million years ago. Nature, 359: 816-818.

Eggins, S., P. De Deckker and J. Marshall (2003), Mg/Ca variation in planktonic foraminifera tests: implications for reconstructing palaeo-seawater temperature and habitat migration. Earth and Planetary Science Letters, 212: 291-306.

Flower, B. P. and J. P. Kennett (1994), The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation and global carbon cycling. Palaeogeography, Palaeoclimatology, Palaeoecology, 108: 537-555.

Grützner, J., M. A. Rebesco, A. K. Cooper, C. G. Forsberg, K. A. Kryc and G. Wefer (2003), Evidence for orbitally controlled size variations of the East Antarctic Ice Sheet during the late Miocene. Geology, 31 (9): 777-780.

Hambrey, M. J. and B. McKelvey (2000), Major Neogene fluctuations of the East Antarctic Ice Sheet: stratigraphic evidence from the Lambert Glacier region. Geology, 28 (10): 887-890.

Harwood, D. M. and P. N. Webb (1998), Glacial transport of diatoms in the Antarctic Sirius Group: Pliocene refrigerator. GSA Today, 8 (4): 4-8.

Heider, F., B. Leitner and H. Inokuchi (1992), High southern latitude magnetostratigraphy and rock magnetic properties of sediments from Sites 747, 749 and 751. In: S. W. Jr. Wise, R. Schlich et al. (Eds), Proceedings of the ODP, Scientific Results, 120: 225-244.

Holbourn, A., W. Kuhnt, M. Schultz and H. Erlenkeuser (2005), Impacts of orbital forcing and atmospheric carbon dioxide on Miocene ice-sheet expansion. Nature, 438: 483-487.

Kennett, J. P. and D. A. Hodell (1995), Stability or instability of Antarctic ice sheets during warm climates of the Pliocene? GSA Today, 5: 1, 10-13, 22.

Lea, D. W., T. A. Mashiotta and H. J. Spero (1999), Controls on magnesium and strontium uptake in planktonic foraminifera determined by live culturing. Geochimica et Cosmochimica Acta, 63 (16): 2369-2379.

Lourens, L. J., F. Hilgen, N. J. Shackleton, J. Laskar and D. Wilson (2004), The Neogene period. In: Gradstein, F. M., Ogg, J. G., and Smith, A. G. (eds) – A Geologic Time Scale 2004: 409-484.

Mashiotta, T. A., D. W. Lea and H. J. Spero (1999), Glacial-interglacial changes in Subantarctic sea surface temperature and δO^{18}-water using foraminiferal Mg. Earth and Planetary Science Letters, 170: 417-432.

Miller, K. G., J. D. Wright and R. G. Fairbanks (1991), Unlocking the Ice House: Oligocene-Miocene oxygen isotopes, eustasy, and margin erosion. Journal of Geophysical Research, 96: 6829-6848.

Pahnke, K., R. Zahn, H. Elderfield and M. Schulz (2003), 340,000-year centennial-scale marine record of Southern Hemisphere climatic oscillation. Science, 301: 948-952.

Reichart, G. J., F. Jorissen, P. Anschutz and P. R. D. Mason (2003), Single foraminiferal test chemistry records the marine environment. Geology, 31 (4): 355-358.

Rosenthal, Y., E. A. Boyle and N. Slowey (1997), Temperature control on the incorporation of magnesium, strontium, fluorine and cadmium into benthic foraminiferal shells from Little Bahama Bank: prospects for thermocline paleoceanography. Geochimica et Cosmochimica Acta, 61 (17): 3633-3643.

Shackleton, N. J. (1974), Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: isotopic changes in the ocean during the last glacial. Colloques Internationaux du C.N.R.S., 219: 203-209.

Shevenell, A. E. and J. P. Kennett (2004), Paleoceanographic change during the Middle Miocene Climate Revolution: an Antarctic stable isotope perspective. In: Exon, N. F., Kennett, J. P., and Malone, M. J. (eds) – The Cenozoic Southern Ocean: tectonics, sedimentation, and climate change between Australia and Antarctica, Geophysical Monograph Series, AGU, 151: 235-251.

Shevenell, A. E., J. P. Kennett and D. W. Lea (2004), Middle Miocene Southern Ocean cooling and Antarctic cryosphere expansion. Science, 305: 1766-1770.

Stroeven, A. P., L. H. Burckle, J. Kleman and M. L. Prentice (1998), Atmospheric transport of diatoms in the Antarctic Sirius Group: Pliocene deep freeze. GSA Today, 8 (4): 4-5.

Webb, P. N. and D. M. Harwood (1991), Late Cenozoic glacial history of the Ross Embayment, Antarctic. Quaternary Science Review, 10: 215-223.

Woodruff, F. and S. M. Savin (1991), Mid-Miocene isotope stratigraphy in the deep sea: high-resolution correlations, paleoclimatic cycles, and sediment preservation. Paleoceanography, 6 (6): 755-806.

Wright, J. D. and K. G. Miller (1992), Miocene stable isotope stratigraphy, Site 747, Kerguelen Plateau. In: S. W. Jr. Wise, R. Schlich et al. (Eds), Proceedings of the ODP, Scientific Results, 120: 855-866.

Zachos, J. C., M. Pagani, L. Sloan, E. Thomas and K. Billups (2001), Trends, rhythms and aberrations in global climate 65 Ma to present. Science, 292: 686-693.