Sediment accumulation rates from the Ross Sea continental shelf and deepwater sites around Antarctica: A physical proxy for the onset of polar conditions

Samuel W. Gray and Philip J. Bart

Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803, USA (sgray1@lsu.edu, pbart@lsu.edu)

Summary During the Cenozoic, the climate progressed from global warmth into an icehouse world. The present day cold Antarctic ice sheet produces little basalt melt water, in contrast to temperate glaciers. Therefore, the transition from temperate to polar conditions should have resulted in marked decrease in sediment delivery to adjacent margins. In this study, sediment accumulation rates were calculated from the Ross Sea outer continental shelf and proximal deepwater Ocean Drilling Program and Deep Sea Drilling Project sites. The compilation of sedimentation rates showed most sites experienced a significant decrease following the middle Miocene cooling and again in the late Pliocene. The abrupt shifts in sediment accumulation rate may represent transitions to largely dry-based conditions for the Antarctic ice sheet at these times, separated by an intervening return to warmer conditions in the Pliocene.

Citation: Gray, S.W. and P.J. Bart (2007), Sediment accumulation rates from the Ross Sea continental shelf and deepwater sites: A physical proxy for the onset of polar conditions, 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, Extended Abstract 140, 4 p.

Introduction

Cenozoic climate can be characterized by a progressive shift from a greenhouse to an icehouse world. Conventional interpretations of composite $\delta^{18}O$ records suggest Antarctica's climate evolved through stepped declines that were punctuated by periods of relative warming (Zachos et al., 2001; Miller et al., 2005). After the "Early Eocene Climatic Optimum" Southern Ocean sea surface temperatures fell from 15 to 6 °C (Zachos et al., 1994). This gradual decline was followed by abrupt ice sheet expansion and cooling associated with the Antarctica's first full-scale ice-sheets in the Early Oligocene (Zachos et al., 1996). These were largely wet-based and are known to have expanded and contracted on Milankovitch time-scales from Oligocene-Early Miocene (33-17 Ma) sedimentary cycles cored off the Victoria Land coast (Naish et al., 2001a,b; Dunbar et al., in press). Terrestrial pollen associated with these sediments indicate coastal summer temperatures ranging between 4 and 12ºC (Raine & Askin, 2001), compared with summer temperatures of today (Barrett, in press). A review of the deep-sea oxygen isotope record for the late Oligocene and early Miocene also indicates large fluctuating ice sheets in a comparable in size to that of today though in a warmer world (Pekar et al. 2006; Pekar and DeConto, 2006). The brief global warming of the Middle Miocene Climatic Optimum (MMCO) was followed by the Middle Miocene Shift (MMS), which is characterized by 3 to 5°C of cooling (Shevenell et al., 2004) and led to the development of a persistent continental AIS (Zachos et al., 2001). Stratigraphic evidence indicates that AIS expanded onto the Ross outer continental shelf through Miocene times (Chow and Bart, 2003), while significant melt water pulses recorded in Wright Dry Valley suggest largely wet basal conditions persisted until between 14.4 and 12.4 Ma (Lewis et al., 2006). Shortly after this event it seems the AIS crossed a thermal threshold, reflecting a transition from largely wet-based conditions to the largely dry-based or "polar" conditions of today's ice sheet.

Polar conditions are defined from a geological viewpoint by basal ice temperature at or below the melting point in , minimal sediment production, and little or no melt water (Anderson and Ashley, 1991). Based on these criteria, sediment flux is potentially useful in distinguishing largely wet-based and dry-based conditions if long sufficiently dated sedimentary records can be found. Modern sediment accumulation rates vary by orders of magnitude from 200-2000 cm/yr in McBride Inlet, Alaska (Cowen and Powell, 1991), which is fed by a temperate glacier, to 0.05-2cm/yr in polar Prydz Bay and Ross Sea regions, Antarctica (Domack et al., 1991). One would expect that the onset of polar conditions would lead to a diminishing sediment flux (Anderson and Ashley, 1991), hence decreasing sediment accumulation both on and off the shelf.

In low latitude basins, the sequence stratigraphic paradigm indicates the highest rates of sediment accumulation occur during rapid relative sea level fall (Vail et al., 1977). Increase and decrease in the volume of land-based ice is the only known mechanism by which sea level changes by meters to tens of meters on time scales of centuries to millennia. The likely wet-based nature of the first ice sheets is presumed to have increased accumulation rates on the outer continental shelf and adjacent deep-water locations. However, the mid and low latitude trends might be expected to depart from those in Antarctica once the AIS became a largely dry-based polar system.

In this study, we calculated and compiled sediment accumulation rates from the Antarctic margin and compared these against global trends to test our hypothesis that sedimentation rates were faster during times when the AIS was extensively wet-based than when it was largely dry-based. This approach also offers potential for establishing the timing of shifts between extensively wet-based and largely polar conditions on Antarctica.

Materials and methods

Published terrigenous sediment mass curves from middle and low latitude oceans (Hay et al., 1988) were used as a baseline of the global trend. This estimate was based on 5 million year (m.y.) intervals. Mass accumulation rates from the Ross Sea outer continental shelf were calculated from sediment volumes inferred from seismically derived isopach maps published as part of ANTOSTRAT (1995) using ESRI ArcMap. The volumes were transferred to masses by correcting for an average wet bulk density of 1850kg/m^3 obtained from ODP Site 1096. Bulk deepwater sediment accumulation rates were calculated from DSDP and ODP cores from the continental rise and proximal abyssal plain. These sites were chosen for their preservation of Miocene strata and proximity to the shelf. Sedimentation rates were calculated in m/m.y. by dividing the difference between adjacent age-depth data points. The ages used for the calculations were determined using published interpretations of paleomagnetic and biostratigraphic data from ODP and DSDP volumes.

Results

Global

Mass accumulation rates of terrigenous sediment in global oceans from Hay et al. (1988) indicate increasing rates from the Late Oligocene to present, which is consistent with the view of overall sea level fall. Rates increase at a constant rate from 1.3x10^{18} kg/m.y. at 25 Ma to 2.0x10^{18} kg/m.y. at 5 Ma before abruptly increasing to 4.2x10^{18} kg/m.y. in the past 5 m.y.

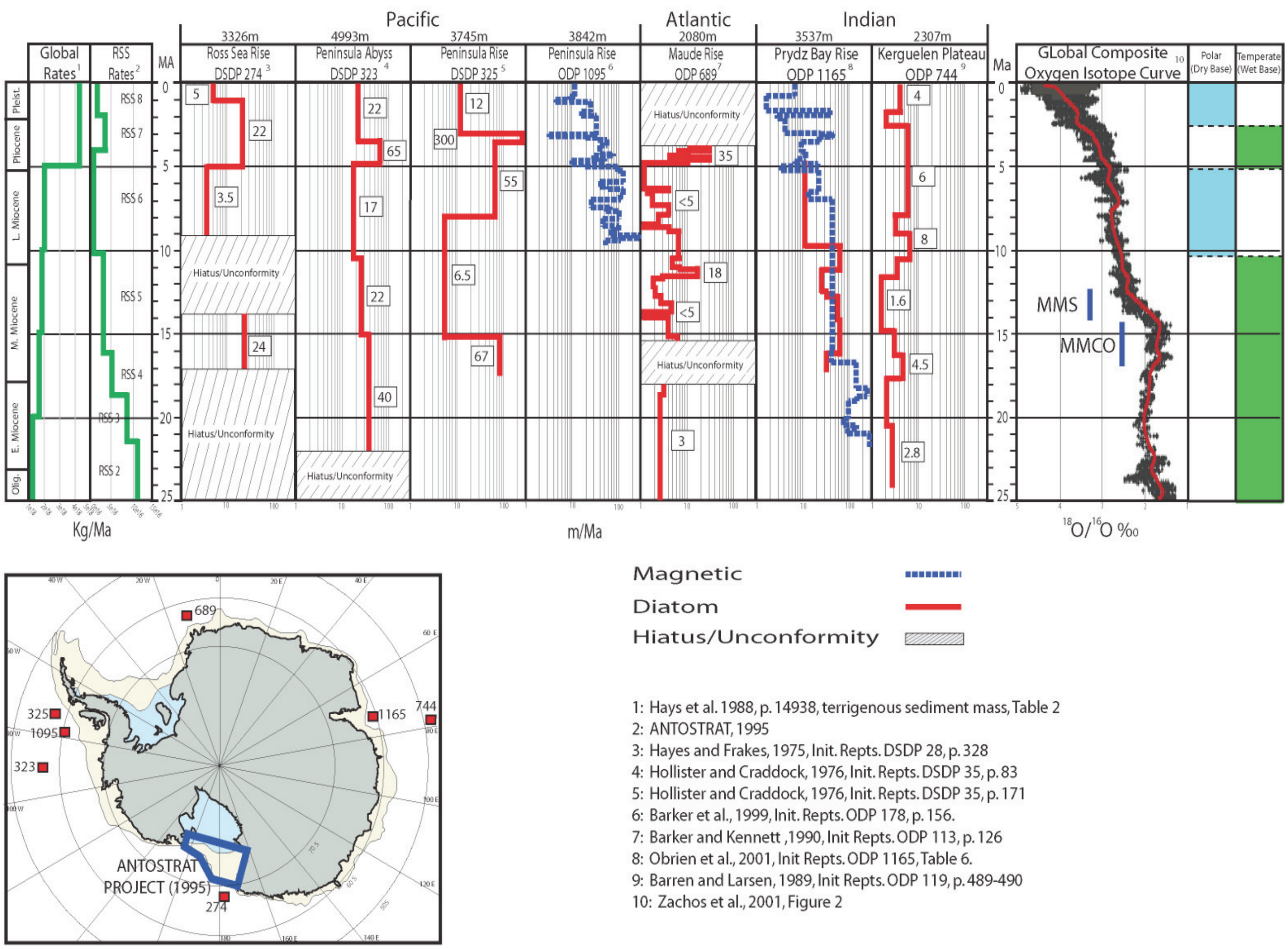

Figure 1. Sediment mass accumulation rates through time around Antarctica

Pacific Margin

The Ross Sea outer continental shelf units are numbered RSS1 (pre-Oligocene) to RSS8 (Pleistocene). Their sedimentation rates decrease from highest at 12x10^{16}kg/m.y. in the Late Oligocene (RSS2) to a low 2.0x10^{16}kg/m.y. in the Pleistocene (RSS8), but the lowest is for the late Miocene and earliest Pliocene (RSS6) at 0.8x10^{16}kg/m.y.. Following this low the late Pliocene (RSS7) shows a significant increase in accumulation (3.8x10^{16}kg/m.y.). A subsequent decrease occurs in the Pleistocene (RSS8), although rates were still a factor of two greater than the low rates of the Late Miocene.

Deepwater sites from the Pacific Margin include Leg 28 site 274, Leg 35 sites 323 and 325 and Leg 178 site 1095. While sparse age control and poor recovery plague sites 274, 323, and 325, some overall trends can be observed. Site 274 on the Ross Sea continental rise records two distinct intervals of sediment accumulation, a Middle Miocene interval with a sedimentation rate of 24m/m.y. and a Late Miocene to present interval, with rates of 3.5 m/m.y. in the Late Miocene, 23m/m.y. in the Pliocene and Early Pleistocene, and 5m/m.y. in the Late Pleistocene. The record at this site is interrupted by two unconformities that created hiatuses from 9 to 14 Ma and 17 to 29 Ma. Site 323, on the Bellinghausen Abyssal Plain, records a continual albeit slight decrease in rates from the Early Miocene to latest Miocene (40 to 17m/m.y.). Rates increase in the early Pliocene to 65 m/m.y. before dropping to 22m/m.y. in the late Pliocene and Pleistocene.

Site 325 on the continental rise of the Antarctic Peninsula indicates variable sediment accumulation rates. At the bottom of the core (17.5 Ma) a rate of 67m/m.y. is recorded, although the rate falls to 6.5 m/m.y. in the mid middle Miocene and early late Miocene. Rates increase to 55 m/m.y. in the latest Miocene and early Pliocene, and subsequently increased to 300 m/m.y., before falling to 12 m/m.y. during the latest Pliocene and Pleistocene. Site 1095, on a rise drift off the Antarctic Peninsula, has a high-resolution record of variable and high sedimentation ranging from >100 to 25 m/m.y. in the late Miocene to 80 to 3 m/m.y. during the Plio-Pleistocene. The overall trend for this interval shows variations superimposed on overall decreasing rates.

Atlantic Margin

ODP leg 113 Site 689, located on the crest of Maud Rise, is the only core from the Atlantic margin. The site records low sedimentation with only slight variations from latest Oligocene to the Pliocene. A 2.8 m.y. hiatus occurred between the early and middle Miocene. Rates calculated were generally low (1 to 7m/m.y.), but higher rates were recorded in the middle Miocene (18m/m.y.) and the early Pliocene (35 m/m.y.).

Indian Margin

Cores from the Indian Margin were Leg 188 Site 1165, Leg 119 Site 744, and Site 1165 on the Prydz Bay continental rise. They contain an uninterrupted sedimentary record from the early Miocene to present. This record indicates variable but an overall decrease in rates from 78 to 300m/m.y. in the early Miocene to 1 to 8m/m.y. in the Pleistocene. Site 744 the southern flank of Kerguelen Plateau records low sedimentation rates with only slight variations (1.5 to 8 m/m.y.) from latest Oligocene to present.

Discussion

The mismatch between the overall Antarctic trends and global trends suggests that sea level was not the ultimate control of sedimentation rates in Antarctica. Our compilation of rates indicates high accumulation rates during the Middle Miocene and Early Pliocene. Conversely, the Late Miocene, and Late Pliocene to Pleistocene are dominated by relatively low accumulation rates, consistent with present day polar conditions. Early Pliocene rates are substantially higher, perhaps because of more extensive basal melting, and are most comparable with those observed for wet-based glaciers like those inferred for the Victoria Land coast in the latest Oligocene and early Miocene (Dunbar et al., in press). On this basis we interpret the shifts to low sedimentation rates observed after the Middle Miocene and Early Pliocene as the sedimentary evidence of polar conditions like today.

Sites 1095 and 1165 located on continental rise drifts depart from the overall pattern, showing an overall decrease through time in intervals that elsewhere show shifts to high sedimentation rates. The lack of low sedimentation rates in the Late Miocene could be explained by differential climate changes across the Antarctic continent (Bart and Anderson, 2000) or by sediment sequestration/bypass. Despite the observed trends from 1095, analysis of opaline silica by Hillenbrand and Erhmann (2005) indicate a cold Late Miocene and Pleistocene, separated by a warm Early Pliocene. Analysis of other Antarctic sedimentary drifts indicated that sedimentation rates were high in the Early Pliocene and decreased in the Pleistocene (Rebesco et al., 2006). Sedimentation rate variations from Kerguelen Plateau and Maud Rise are extremely low and these subtle changes may reflect influence of biogenic sediment as opposed to ice sheet evolution.

While thermal regime and associated basal conditions appear to be the most likely control on Antarctic sedimentation rates, the potential affects of sea level change and ice volume cannot be ignored. Given the opposing trends from Antarctic and global basins, sea level was probably not the dominant control on sediment accumulation. A potential cause for the departure could be the presence of at least ephemeral continental scale ice sheets since the Early Oligocene (Zachos et al., 2001; Miller et al., 2005). Grounded ice is also a potential control on sediment supply. Glacio-eustatic controlled sequence boundaries (Haq et al., 1987) used as a proxy for ice grounding reveal the number of events has increased from pre MMS (TB 1.1-2.3) to post MMS (TB3-3.9). If sedimentation were influenced by ice volume, then one would expect the opposite, suggesting that ice volume is not a significant control on sediment accumulation. The last possibility is that poor data coverage and weak age control have resulted in false trends.

Summary

Sediment accumulation rates from the Antarctic margin suggest polar conditions first became established in the Late Miocene. High rates in the Early Pliocene suggest that warmer basal conditions returned for a period with polar conditions returning in the Late Pliocene. The implications of this study need to be tested with additional Antarctic evidence. When data coverage and quality is improved, a potentially powerful tool will be available to test conventional proxy based climate interpretations in polar settings, and refine the findings of this study.

Acknowledgements. We would like to thank SED and JMC for discussion and advice, and the reviewers and co-editor for their comments.

References

Anderson, J.B. and G.M. Ashley (1991), Glacial marine sedimentation; Paleoclimatic significance; A discussion. in Glacial Marine Sedimentation; Paleoclimatic Significance, edited by J.B. Anderson and G.B.Ashley, Geol. Soc. Am. Spec. Paper, 261, 223–226.

ANTOSTRAT Project (1995), Geology and Seismic Stratigraphy of the Antarctic Margin, Amer. Geophys. Union Antarctic Research Series, 68.

Barrett, P.J. (in press), Cenozoic climate and sea level history from glacimarine strata off the Victoria Land coast, Cape Roberts Project, Antarctica, in Glacial Sedimentary Processes and Products, edited by M.J. Hambrey, P. Christoffersen, N.F. Glasser and B. Hubbart, International Assoc. Sedimentol. Spec. Pub..

Bart, P.J. and Anderson, J.B., 2000, Relative temporal stability of the Antarctic Ice Sheets During the Late Neogene Based on the Minimum Frequency of Outer Shelf Grounding Events, Earth Planet. Sci. Lett., 182, 259-272.

Billups, K. and D.P. Schrag (2002), Paleotemperatures and ice volume of the past 27 Myr revisited with paired Mg/Ca and $^{18}O/^{16}O$ measurements on benthic foraminifera, Paleoceanography, 17, 1003-1014.

Chow, J.M., and P.J. Bart (2003), West Antarctica Ice Sheet grounding events on the Ross Sea outer Continental shelf during the middle Miocene, Palaeogeogr. Palaeoclimatol, Palaeoecol., 198, 169-186.

Cowen, E.A. and R.D. Powell (1991), Ice-proximal sediment accumulation rates in temperate glacial fjords, southeastern Alaska, in Glacial Marine Sedimentation; Paleoclimatic Significance, edited by J.B. Anderson and G.B. Ashley, Geol. Soc. Am. Spec. Paper, 261, 61–73.

Domack, E.W., A.J. Jull and J.D. Donahue (1991), Holocene chronology from the unconsolidated sediments at hole 740A, Prydz Bay, East Antarctica, in J.A. Barron and B. Larsen, ODP Init. Repts., 119, College Station, TX.

Dunbar G.B., T.R. Naish, P.J. Barrett, C.R. Fielding, R.D. Powell (in press), Constraining the amplitude of Late Oligocene bathymetric changes in western Ross Sea during orbitally-induced oscillations in the East Antarctic Ice Sheet: (1) Implications for glacimarine sequence stratigraphic models, Palaeogeogr. , Palaeoclimatol., Palaeoecol.

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, Palaeogeogr., Palaeoclimatol., Palaeoecol., 108, 537-555.

Haq, B.U., J. Hardenbol, and P.R. Vail (1987), Chronology of fluctuating sea levels since the Triassic, Science, 235, 1156-1167.

Hay, W.W., J.L. Sloan and C.N. Wold (1988), Mass/Age Distribution and Composition of Sediments on the Ocean Floor and the Global Rate of Sediment Subduction, J. Geophys. Res., 93, 14933-14940.

Hillenbrand, C.D. and W. Ehrmann (2005), Late Neogene to Quaternary environmental changes in the Antarctic Peninsula regions: evidence from drift sediments: Global Planet. Change, 45, 165-191.

Lewis, A.R., D.R. Marchant, D.E. Kowalewski, S.L. Baldwin, and L.E. Webb (2006), The age and origin of the Labyrinth, western Dry Valleys, Antarctica; Evidence for extensive middle Miocene subglacial floods and freshwater discharge to the Southern Ocean, Geology, 34, 513-516.

Miller, K.G., J.D. Wright and J.V. Browning (2005), Visions of ice sheets in a greenhouse world, Marine Geology, 217, 215-231.

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

Naish, T.R., P.J. Barrett, G.B. Dunbar, K.J. Woolfe, A.G. Dunn, S.A. Henrys, M. Claps, R.D. Powell and C.R. Fielding (2001b), Sedimentary cyclicity in CRP drillcore, Victoria Land Basin, Antarctica, Terra Antartica, 8, 225-244

Pekar, S.F. and R.M. Deconto (2006), High-resolution ice-volume estimates for the early Miocene: Evidence for a dynamic ice sheet in Antarctica: Palaeogeogr. Palaeoclimatol, Palaeoecol., 231, 101-109.

Pekar, S.F., R.M. DeConto, and D.M. Harwood (2006), Resolving a late Oligocene conundrum: Deep-sea warming and Antarctic glaciation. Palaeogeogr. Palaeoclimatol, Palaeoecol., 231, 29-40.

Rebesco, M., R.D. Larter, P.F. Barker, A. Camerlenghi, and L.E. Vanneste (1997), The history of sedimentation on the continental rise west of the Antarctic Peninsula, in Geology and Seismic Stratigraphy of the Antarctic Margin, edited by J.P. Kennett and D.A. Warnke, Amer. Geophys. Union Antarctic Research Series, 71, 29-49.

Rebesco, M., A. Camerlenghi, R. Geletti and M. Canals (2006), Margin architecture reveals the transition to the modern Antarctic ice sheet ca. 3Ma, Geology, 34, 301-304.

Shevenell, A.E., J.P. Kennett and D.W. Lea (2004), Middle Miocene Southern Ocean Cooling and Antarctic Cryosphere Expansion, Science, 305, 1766-1770.

Shipboard Scientific Party (1975), Site 323 and 325, in D.E.Hayes, L.A. Frakes et al., DSDP Init. Repts. 28, Washington

Shipboard Scientific Party (1976), Site 323 and 325, in C.D. Hollister, C. Craddock et al., DSDP Init. Repts. 35, Washington DC.

Shipboard Scientific Party (1989), Site 744, in J.A. Barron, B. Larsen et al., ODP Init. Repts. 119, College Station, TX.

Shipboard Scientific Party (1990), Site 689, in P.F. Barker, J.P. Kennett et al., ODP Init. Repts. 113, College Station, TX.

Shipboard Scientific Party (1999), Site 1095, in P.F. Barker, A. Camerlenghi, G.D. Acton et al., ODP, Init. Repts 178, College Station, TX.

Shipboard Scientific Party (2001), Site 1165, in P.E. O'Brien, P.E., A.K. Cooper et al.., ODP Init. Repts. 188, College Station, TX.

Vail, P.R., R.M. Mitchum, R.G. Todd, J.M. Widmier, S. Thompson, J.B. Sangree, J.N. Bubb, and W.G. Hatelid, (1977), Seismic stratigraphy and global changes of sea level, in Seismic Stratigraphy-Applications to Hydrocarbon Exploration, edited by C.E. Clayton, AAPG Memoir 26, 49-212.

Zachos, J.C., L.D. Stott and K.C. Lohmann (1994), Evolution of early Cenozoic marine temperatures, Paleoceanography, 9, 353-387.

Zachos, J.C., T.M. Quinn and K.A. Salamy (1996), High resolution (10^4 years) deep-sea foraminiferal stable isotope records of the Eocene-Oligocene climate transition, Paleoceanography, 11, 251-266.

Zachos, J., 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.