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High-resolution ice-volume estimates for the early Miocene: Evidence for a dynamic ice sheet in Antarctica

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Abstract

Ice-volume estimates for the early Miocene (23–16 Ma ATS) were determined by applying $\delta^{18}O$ to sea-level calibrations to high-resolution $\delta^{18}O$ records from ODP Sites 1090 and 1218. These calibrated records indicate that ice-volume ranged between 50% and 125% of the present day East Antarctic Ice Sheet (EAIS) during most of the early Miocene (23–17 Ma). Maximum ice-volume occurred at each of the early Miocene isotopic events (i.e., Mi-events) concomitant with bottom water temperatures generally between ~1 and 2 °C. Rapid ($\ll$1 myr) and high amplitude ice-volume changes also occurred intermittently during this period, with some fluctuations ranging from a fully glaciated East Antarctic continent to a partial collapse of the ice sheet (equivalent to a 50–70% reduction in the EAIS). These large-scale ice-volume changes often occurred at <100 kyr time scales suggesting an orbitally driven dynamic EAIS existed during the early Miocene. In contrast, the calibrated $\delta^{18}O$ record from Site 1090 indicates significantly less ice-volume (25–70% of the present-day EAIS) was present between 17 and 16 Ma. These results are supported by numerical climate–ice sheet modeling studies that show increased orbitally driven ice-volume variability with elevated levels of atmospheric CO_2.

The distribution of bottom water masses during the Miocene was likely significantly different from today, owing to variability in the production of deep-water near the Antarctic continent (i.e., proto-Antarctic Bottom Water, proto-AABW). Weakening of proto-AABW is suggested to have occurred during the early Miocene especially during glacial minima, resulting in it becoming more spatially restricted to the Southern Ocean and becoming entrained into a warmer deep-water mass. Increased production of a warmer bottom water mass is also considered to have been important in the lighter isotopic values observed in the Atlantic and Indian Oceans. These changes are supported by evidence of a large dynamic EAIS based on strata cored on the Antarctic margin, and require a reevaluation of the view that Antarctic ice-volume was significantly reduced for most of the early Miocene. Previous estimates have been constrained by the lack of deep-water isotopic records proximal to Antarctica, and unduly influenced by the expansion of warmer deep-water into most of the ocean basins at this time.

Keywords: Antarctica; Ice-volume; Miocene; Sea-level; Oxygen isotopes; East Antarctic ice sheet

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1. Introduction

Deep-sea records show a significant decrease in deep-sea δ^{18}O values in most of the world's ocean basins during the late Oligocene and the early Miocene (e.g., Miller et al., 1987; Wright and Miller, 1993; Zachos et al., 2001). These low isotopic values have been attributed to deep-sea warming, along with a substantial decrease to a near complete collapse of the Antarctic ice sheet (e.g., Zachos et al., 2001). The only exceptions were indicated by positive δ^{18}O increases interpreted to represent transient ice-volume expansion in Antarctica (i.e., Mi-events, Miller et al., 1991). This warming in Antarctica was supported by isotopic evidence from most ocean basins indicating that the source of bottom water emanated mainly from a Southern Ocean source (i.e., Southern Component Water, SCW), presumably originating from coastal waters around the Antarctic margin (e.g., Wright and Miller, 1993). This suggested that bottom waters, including those from lower latitude sites, can serve as a proxy for paleoenvironmental conditions on the Antarctic continent.

In contrast, results from recent drilling on the Victoria Land margin of the Ross Sea, Antarctica (e.g., CIROS, Cape Roberts Project) indicate a cool climate in the Ross Sea through the Oligocene (Raine and Askin, 2001; Thorn, 2001; Prebble et al., this volume), with cold tundra-like conditions becoming established by the early Miocene (Raine and Askin, 2001). Furthermore, glacigenic sediments recovered in latest Oligocene and early Miocene strata from the Ross Sea indicate that some regions (if not all) of East Antarctica were sufficiently cold for ice sheets to reach sea-level during glacial maxima (Barrett et al., 1987; Naish et al., 2001) and relatively cold climates during glacial minima, similar to the high altitude of Patagonia today (Hill, 1989). Furthermore, ice grounding lines appear to have reached near the shelf edge as the early Miocene in the Ross Sea as early and in Prydz Bay by the early Oligocene (Cooper et al., 1991; Bartek et al., 1997), supporting the notion of large continental ice sheets on East and possibly West Antarctica at this time.

Higher δ^{18}O values from a recently developed record at early Miocene Site 1090 have been used to suggest that more ice may have existed than previously thought during this time (Billups et al., 2002). These higher values are, in part, attributable to Site 1090's location. Site 1090 is the deepest early Miocene site in high southern latitudes with an isotopic record. Therefore, this location has the best chance of being bathed by cold dense Antarctic water (e.g., proto-Antarctic Bottom Water, proto-AABW) (Billups et al., 2002). Unfortunately, isotopic records proximal to Antarctica or from other deep-water sites in the Southern Ocean that could be used to evaluate proto-AABW characteristics are lacking. This is due, in part, to the occurrence of hiatuses at many Southern Ocean sites (e.g., Sites 689 and 690) during the late Oligocene and early Miocene (Wright and Miller, 1993; Zachos et al., 2001).

While recently published studies have made use of Mg/Ca ratios combined with δ^{18}O data to estimate ice-volume during the early Miocene, a number of uncertainties in temperature estimates from Mg/Ca ratios have been noted. These include possible pH-related changes in Mg partitioning into calcite associated with changes in the calcium compensation depth (CCD), possible oceanic Mg/Ca ratio changes through time, isotopic species offset, and diagenesis (e.g., Billups and Schrag, 2003; Lear et al., 2004). Therefore, constraints on the relative contribution of temperature and ice-volume in isotopic values remain uncertain, further clouding our understanding of early Neogene cryospheric evolution.

This paper provides constraints on ice-volume changes in Antarctica and global sea-level changes in the early Miocene by applying δ^{18}O to sea-level calibrations to δ^{18}O records from Sites 1090 and 1218. Here, we argue that ice-volume was greater in Antarctica (from 50% up to 125% of the present-day EAIS) during the early Miocene (23–17 Ma) than previously believed.

2. Methods, definitions, data, and sites used

In this study, calibrated δ^{18}O records from ODP Sites 1090 and 1218 were used to estimate changes in Antarctic ice-volume and global sea-level changes (Fig. 1) (Billups et al., 2002; Lear et al., 2004). The age models for Sites 1090 and 1218 are based on an astronomically tuned age model (from Billups et al., 2004; Lear et al., 2004) and the astronomical time scale of Shackleton et al. (1999). The new time scale shifts the Miocene/Oligocene boundary to 23.0 Ma from the long recognized age of 23.8 Ma of the Berggren et al. (1995) time scale. Ages for isotopic events of Miller et al. (1991) were converted to the new time scale using the revised ages for the early Miocene and late Oligocene polarity chron boundaries from Billups et al. (2004).

Here, we use the term apparent sea-level (ASL) to define eustasy plus water loading effects on the crust (Pekar et al., 2002). As sea-level either rises or falls, and flooded portions of the crust experience water loading or unloading, observed fluctuations in water depth relative

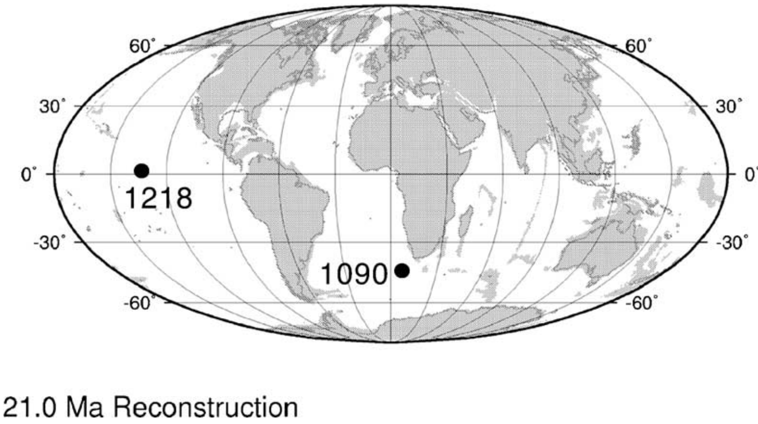

Fig. 1. Plate reconstructions circa 21 Ma showing paleo locations of ODP Sites 1090 and 1218.

to the ocean floor exceed the eustatic changes by a factor of ~1.48 (Kominz and Pekar, 2001). Changes in ASL are solely of eustatic origin, but they differ in amplitude because their reference frame is different. In the case of eustasy, the reference point is the center of the Earth, while for ASL, it is a point in the crust after flexural subsidence from sediment loading, crustal cooling and compaction have been taken into account.

Deep-sea isotopic measurements are typically obtained using single species, such as *Cibicidoides* spp. However, *Cibicidoides* spp., like most other benthic foraminifers, precipitate their tests out of equilibrium with calcite (δ^{18}O values in the tests of *Cibicidoides* spp. are offset with respect to calcite by +0.64‰). Oxygen isotope records from both sites have been adjusted to represent the isotopic value of calcite.

The δ^{18}O record from ODP Site 1218 was calibrated to sea-level by comparing benthic foraminiferal δ^{18}O amplitudes for δ^{18}O events (i.e., Oi- and Mi-events; Miller et al., 1991; Pekar and Miller, 1996) from this site to ASL amplitudes using detrended ASL estimates from Pekar et al. (2002). The detrended ASL estimates were derived by integrating two-dimensional flexural backstripping (Kominz and Pekar, 2001) with two-dimensional paleoslope modeling of foraminiferal biofacies and lithofacies (Pekar and Kominz, 2001). This provided a calibration of 0.16‰/10 m ASL (r^2=0.67). Previously reported calibrations for other DSDP and ODP Sites were good to excellent, with the correlation coefficient (r^2) of the regressions ranging from 0.73 to 0.99 (Pekar et al., 2002, this volume). These correlations suggest that although benthic foraminiferal records are assumed to contain a significant bottom-water temperature signal, decreasing temperature produces a nearly linear increase in ice-volume estimates. The calibration for Site 1090 uses a single δ^{18}O event (Mi1, 23.0 Ma). The ASL estimate of 56 ± 25 m from Pekar et al. (2002) results in a calibration ranging from 0.19‰ to 0.48‰ (0.34 ± 0.14‰ mean calibration) per 10 m ASL. Therefore, all ASL estimates from Site 1090 include an uncertainty of ± 0.14 ‰ per 10 m of ASL change.

Although previous calibrations indicate that temperature scales linearly with respect to ice volume, uncertainties may exist due to temperature variability. For example, bottom water temperature changes could occur outside the variability suggested by the calibrations for a given site as a result of long or short-term changes in deep-sea circulation patterns. Additionally, ASL estimates from high δ^{18}O values (≥ 3‰) are considered more robust and are consistent with a fully glaciated East Antarctic continent and cold bottom water temperatures, since lower δ^{18}O values could have a wider range of possible ice-volume and bottom water temperatures. For example, the highest values at Site 1090 are consistent with an ice sheet up to ~25% larger than the present-day EAIS and bottom water temperatures slightly colder than waters currently bathing Site 1090 (Billups et al., 2002). Invoking smaller ice volume with these values would require the unlikely situation of substantially colder bottom waters during the early Miocene than today, the former being a time of warmer climate and polythermal ice sheets over Antarctica in contrast to the present cold polar conditions.

We suggest early Miocene δ^{18}O values of 3‰ or greater in deep-sea records are consistent with an EAIS of modern proportions and cold bottom water temperatures (≤2.0 °C). The average modern *Cibicidoides* spp. value in ~2.0 °C waters is 2.7‰ (Shackleton and Kennett, 1975) or 3.34‰ adjusted for equilibrium with calcite. Of that value, the contributions from the present-day ice sheets are estimated to range from ~0.9‰ to 1.2‰ (Miller et al., 1991; Zachos et al., 2001). In this study, the isotopic contribution of the present-day ice sheets is estimated to be ~1.0‰, based on modern ice-volume estimates of both grounded ice and ice below sea-level (Williams and Ferrigno, 1999). Of that 1.0‰ value, 0.13‰ is attributed to ice from Greenland and West Antarctica (Pekar et al., this volume). During the early Miocene, Greenland and West Antarctica may not have been glaciated, reducing this average deep-sea δ^{18}O value by 0.13‰. Furthermore, ice in the poly-thermal EAIS of the early Miocene most likely had significantly higher δ^{18}O values in the ice sheet (e.g., ~−35‰) than values today (i.e., −45‰ to −55‰). Higher than modern isotopic values in early Miocene polar precipitation and glacial ice is supported by floral evidence showing that the Ross Sea region was significantly (>9 °C) warmer during the late Oligocene and early Miocene than it is today (Prebble et al., this volume). This would have further reduced the isotopic value contribution of ice to the mean isotopic value of the oceans by 0.25‰ during the Miocene (Pekar et al., this volume). This results in an isotopic value of ~3‰ being consistent with calcite forming in 2 °C waters during the early Miocene, concomitant with a fully glaciated East Antarctic continent.

Uncertainties in this value could include the potential effects of salinity. The range in salinity between water masses in the deep sea today (e.g., North Atlantic Deep water [34.95‰] and Antarctic Bottom Water [34.65‰]) is about 0.3‰, which would result in an isotopic uncertainty of ±0.1‰. A warmer deep-water mass with a higher salinity would have a higher δ^{18}O value on this account, resulting in an overestimate in ice volume. In contrast, colder deep-waters with lower salinity, such as proto-AABW, would have a lower δ^{18}O, resulting in an underestimate of the ice volume. Also, the isotopic value of the ice should vary between glacial maxima and minima, which could result in an additional uncertainty that would be equivalent to perhaps 5 to 10 m of sea-level change.

Recent studies have suggested that West Antarctica and perhaps even northern hemisphere continents may have been glaciated during the Miocene (e.g., Coxall et al., 2005). However, if a West Antarctic Ice Sheet (WAIS) existed during the Miocene, its isotopic contribution would be minor (0.06‰). Furthermore, the presence of northern hemisphere ice-volume during the Paleogene and early Miocene is controversial with little evidence from the northern hemisphere fauna, flora, or lithological studies to support it (e.g., Wolfe, 1978; Axelrod and Raven, 1985; Tiffney, 1985). However, if a fully developed Greenland ice sheet did form during the early Miocene, it would increase the isotopic value of the global oceans by 0.07‰ and if combined with the WAIS could be invoked to explain a small fraction of the larger ice-volume estimates recently proposed for the Oligocene and early Miocene (equivalent to 80 m ASL, Kominz and Pekar, 2001; 90 m ASL Lear et al., 2004; 100 to 160 m ASL, Coxall et al., 2005).

In calibrating δ^{18}O records to ASL, Mi-events provide a means for estimating temperature gradients between the two sites. Site 1090 typically contains higher δ^{18}O values than Site 1218 during Mi-events, therefore the calibrated record from Site 1218 was adjusted to account for the isotopic offset with the highest value observed at each event. For example, at Mi1, values at Site 1218 are ~0.4‰ lighter than Site 1090, which is assumed to be due to warmer bottom waters bathing Site 1218. Bottom water temperature changes are constrained by subtracting the ice-volume contribution (estimated to be 0.091‰/10 m ASL; DeConto and Pollard, 2003) from the δ^{18}O to sea-level calibration. As noted above, this is based on the assumption that early Miocene Antarctic temperatures were warmer than today, resulting in an average isotopic composition of the ice sheet of −35‰. The average calibration for Site 1090 of 0.34‰ per 10 m ASL suggests that approximately 75% of the isotopic change during the Miocene is due to temperature. In contrast, the lower calibration for Site 1218 (0.16‰/10 m ASL) suggests that the temperature signal was smaller (~45%) than at Site 1090.

3. Early Miocene ice-volume changes

Applying these calibrations to δ^{18}O records from Sites 1090 and 1218 indicate ice volume ranged from a fully glaciated East Antarctic continent to major reductions of the ice sheet in the early Miocene. The record from Site 1090 is characterized by values often near or above 2.9‰, which are consistent with a heavily glaciated East Antarctica (Fig. 2). The isotopic values ≥3.3‰ occurring at 23.0, 21.2, 21.1, 20.4 Ma correlate well with Mi-events of Miller et al. (1991): Mi1 (23.0 Ma); Mi1a (21.1 Ma); and Mi1aa (20.2 Ma, ATS, Shackleton et al., 1999). Using the calibrated records, these values are consistent with an ice sheet up to 25% larger than the present-day EAIS and bottom water temperatures ranging from ~2 °C to as low as 0.7 °C. Two additional isotopic increases culminating with values of 2.9‰ in the latter portion of the early Miocene at 18.4 and 17.8 Ma correlate with the Mi1ab and Mi1b events, respectively. These large ice-volume estimates are partly supported by glacial grounding lines that extend out to the outer shelf of Antarctica by the earliest Oligocene in Prydz Bay and early Miocene in the Ross Sea (Cooper et al., 1991; Bartek et al., 1997).

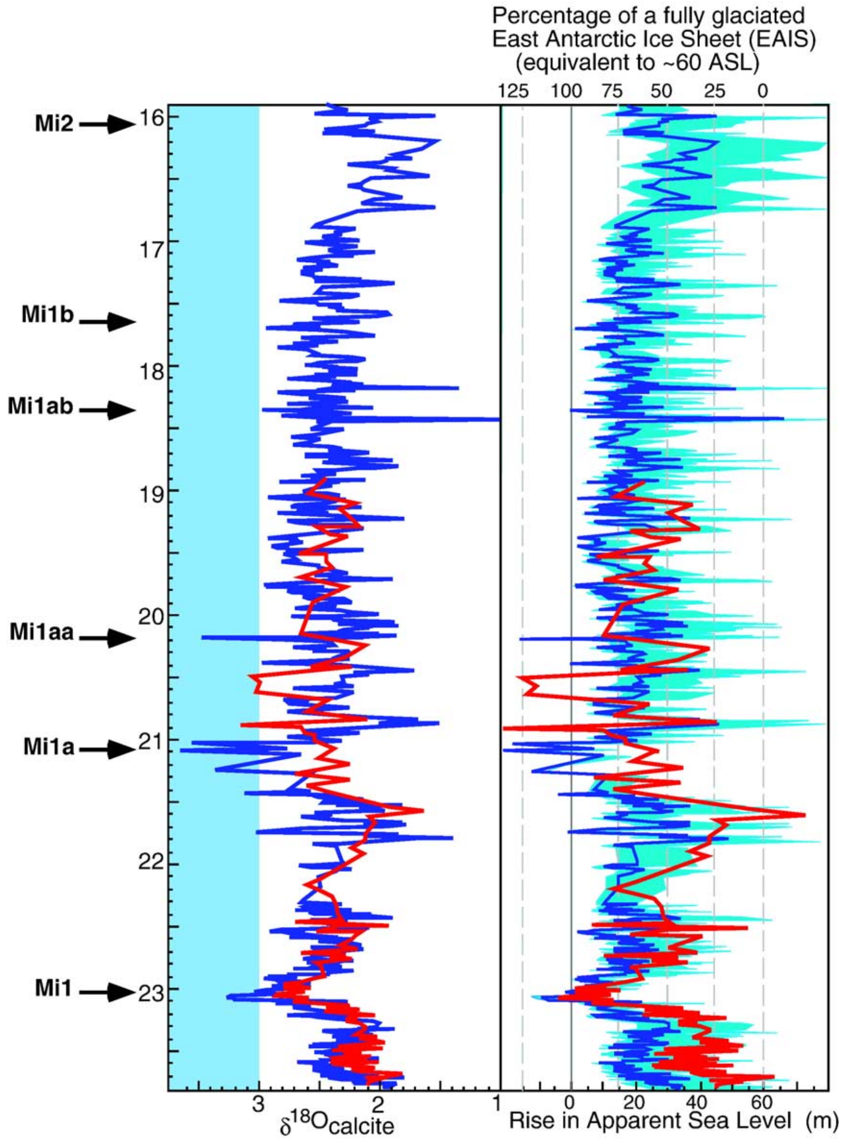

Fig. 2. Oxygen isotope records from Sites 1090 (in blue) and 1218 (in red). Oxygen isotope events (i.e., Mi-events) are shown (from Miller et al., 1991 and calibrated to the ATS of Shackleton et al., 1999). Apparent sea-level estimates from Site 1090 for the early Miocene are from δ^{18}O to apparent sea-level calibration of 0.34‰ per 10 m ASL, shown in a thick dark blue line. The range in sea-level estimates is also shown in shaded areas. In red are ice-volume estimates using the calibrated records from Site 1218. Ages are based on astronomical time scales from Shackleton et al. (1999) and Billups et al. (2004).

These ice-volume estimates are somewhat greater than recent GCM-ice sheet simulations of the Oi1 event (DeConto and Pollard, 2003), which ignored significant ice on West Antarctica or the seaward expansion of grounding lines beyond the model shorelines, and are closer to simulations of maximum Antarctic ice-volume during Quaternary glacial periods (Ritz et al., 2001), when the total area of grounded ice on East and West Antarctica was 15–25% greater than today (e.g., Denton and Hughes, 2002; Huybrechts, 2002).

Early Miocene δ^{18}O values varied in some cases up to 2‰ suggesting large fluctuations in both ice-volume and bottom water temperatures. Furthermore, low isotopic values ranging from 1.7‰ to as low as 0.9‰ at 21.8, ~20.8, 20.4, 18.4, 18.2 Ma at Site 1090 are consistent with a significant reduction of the east Antarctic ice sheet ($\geq$50% of the present day EAIS) and bottom water temperatures of ~5 to 8 °C. These large isotopic shifts are unprecedented for Paleogene isotope records (with the exception of the Oi1 event at the base of the Oligocene) or afterward (until the Pleistocene) and suggest considerable variability in ice volume as well as bottom water temperature. These collapses occurred in some cases within 100 kyr of the ice-volume maximum. These large, high-frequency ice-volume amplitudes suggest a more dynamic cryosphere existed in the early Miocene than had been estimated for the Oligocene from the deep-sea isotopic record, in which high-frequency ice-volume changes (i.e., ≤100 kyr) rarely exceeded 25–30% of the present-day ice sheet (Pekar et al., this volume).

Ice-volume lower than the estimates presented here are possible if the isotopic composition of the early Miocene ice sheet was lower than the values used here (−50‰ present-day values versus −35‰ estimated for the early Miocene). A further overestimation of the ice sheet could occur if lower bottom water temperatures were present. However, using the calibrated records presented here, water temperature estimates are already low (0.7 °C), and in fact are lower than water temperatures currently bathing Site 1090 (~1.2 °C, Billups et al., 2002). Bottom water temperatures during times of a polythermal ice sheet being colder than during today's extreme polar conditions are unlikely, and support the idea that ice-volume during the early Miocene were as large as the estimates presented here.

4. Implications for deep-sea water mass changes

High $\delta^{18}O$ values at Sites 1090 and 1218 suggest that a cold water mass (e.g., proto-AABW) existed in the far southern Atlantic and abyssal Pacific basins. These waters appear to have spread and then mixed with other water masses during much of the early Miocene (Fig. 3) (Billups et al., 2002; Lear et al., 2004). In contrast, significantly lower $\delta^{18}O$ values at other deep-sea sites indicate that a warmer deep-water mass bathed most of the Atlantic and Indian Ocean basins (Fig. 3). This warmer deep-water mass has been previously recognized by others (e.g., Woodruff and Savin, 1989; Wright et al., 1992; Wright and Miller, 1993; Billups et al., 2002) and has been suggested to have a Tethyan or northern Atlantic origin as it appears that the warmest waters occurred at deep and intermediate water depths in the Atlantic Ocean (Fig. 3) (e.g., Woodruff and Savin, 1989; Wright et al., 1992; Wright and Miller, 1993). Differences in $\delta^{18}O$ values between proto-AABW (at Sites 1090 and 1218) and deep-waters from other ocean basins suggest a temperature gradient of up to 6 °C during glacial periods (Fig. 3), which is larger than observed today (~3–4 °C) (Wright and Colling, 1995). It should also be noted that values from Site 1218 are lighter than Weddell Sea Site 690 during the late Oligocene. This suggests that values from both sites 1090 and 1218 may not be representative of the highest isotopic values, especially during glacial minima (Pekar et al., this volume) and may indicate that even higher bottom water gradients could have existed during the early Miocene. This large gradient can be reconciled by proto-AABW being restricted during the early Miocene, becoming entrained with a warmer deep-water mass originating from the Atlantic and Indian Oceans.

The large fluctuations in $\delta^{18}O$ values, especially at Site 1090, suggest significant variability in the production of proto-AABW. During glacial maxima (i.e., Mi-events), the close proximity of the ice sheet to the

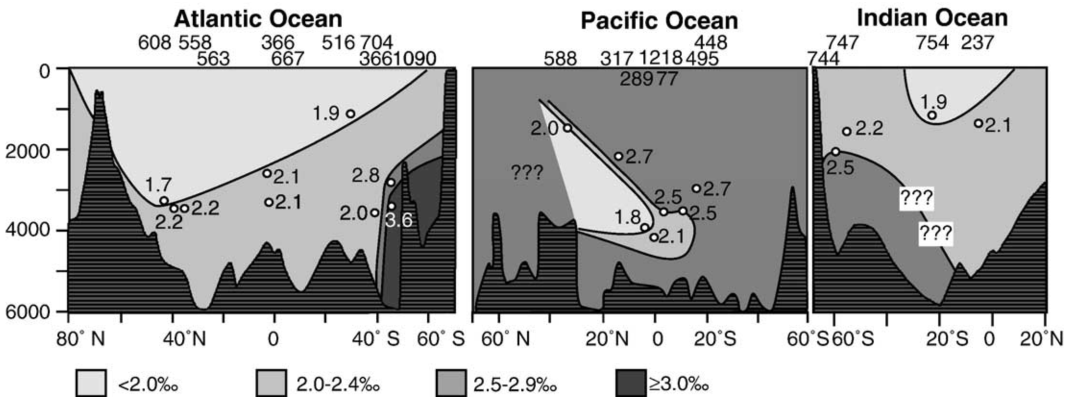

Fig. 3. Time slice for 21.2–20.8 Ma (circa $\delta^{18}O$ event Mi1a) showing an isotopic transect for the Atlantic, Indian, and Pacific Oceans. DSDP and ODP sites used here are labeled in the upper portion. Paleodepths for each site are indicated by a circle and are from Wright and Miller (1993) and Woodruff and Savin (1989). Maximum $\delta^{18}O$ values within the 400-kyr time slice are shown next to circles. Deep-sea sites (e.g., Sites 689, 690, 744) proximal to Antarctica contain significant hiatuses for large portions of the early Miocene (Wright and Miller, 1993). Lower values in the northern Atlantic, northern Pacific and Indian Oceans suggest warmer deep-waters may have been forming in these basins.

coastline could have enhanced production of proto-AABW from cooling of surface water as well as formation of sea ice, both of which play an important role today in the creation of Antarctic Bottom Water (Wright and Colling, 1995). In contrast, during glacial minima, retreat of an ice sheet into the continental interior would result in warmer surface water temperatures and a reduction in sea ice forming along the coast, which would most likely affect proto-AABW production. Furthermore, additional runoff from a retreating ice sheet during interglacials would result in a freshening of the coastal waters around Antarctica, possibly further weakening proto-AABW production.

During glacial periods, proto-AABW extended outwards, reaching Sites 1090 and 1218 and then mixing with a warmer bottom water mass. In contrast, during glacial minima, proto-AABW production weakened, resulting in cold deep-waters that became more spatially restricted, with warmer deep-waters expanding over abyssal and high southern latitude areas, such as at Sites 1090 and 1218. Increased production of proto-AABW during glacial maxima is supported by deep-sea hiatuses in the Southern Ocean during each early Miocene Mi-event, which has been ascribed to enhanced bottom water formation (Carter et al., 2004). Evidence for expansion and strengthening of warmer deep waters originating from the northern Atlantic Ocean is suggested by isotopic evidence that indicates a "turning on" of a deep-water mass originating from the North Atlantic during the early Miocene (Wright et al., 1992; Wright and Miller, 1993, 1996). These paleoceanographic changes are supported by numerical modeling studies designed to test the effects of the opening and deepening of the Drake Passage (Mikolajewicz et al., 1993; Toggweiler and Samuels, 1995; Nong et al., 2000; Toggweiler and Bjornsson, 2000; Huber et al., 2004; Sijp and England, 2004). The Southern Ocean gateways were likely the final barrier to circum-Antarctic circulation (Lawver and Gahagan, 1998; Livermore et al., 2004). While the precise timing of tectonic events in the Scotia Sea remains controversial, a deep-water passage likely became established no later than the earliest Miocene (Barker and Burrell, 1977; Livermore et al., 2004). These studies indicate that with an open and deep Drake Passage, Southern Ocean deep-water formation (proto-AABW) would be reduced, northern Atlantic deep-water formation would increase, in conjunction with cooling of high southern latitudes (e.g., Sijp and England, 2004).

The full spatial extent and strength of the proto-AABW during the early Miocene is uncertain as most southern deep-sea sites (e.g., Sites 689 and 690) with isotopic records contain significant hiatuses during this time (e.g., Wright and Miller, 1993). Coring the stratal record from the Ross Sea margin of Antarctica is planned for providing new data to address these issues (http://andrill/org/).

5. Conclusions

Ice-volume for much of the early Miocene (23–17 Ma) has been estimated to be equivalent to between 50% and 125% of the present-day EAIS, based on application of $\delta^{18}O$ to sea-level calibrations for high-resolution records from ODP Sites 1090 and 1218. In contrast, significant reductions in ice volume (>50% of the present-day EAIS) coeval with a bottom water temperature increase of at least 4 °C, based on low $\delta^{18}O$ values (<1.7‰), occurred episodically between 22 and 18 Ma and more generally between 16.7 and 16.0 Ma. In some cases, these large fluctuations occurred in <100 kyr supporting the view that a dynamic ice sheet existed during the early Miocene.

Cold deep-water originating from near Antarctica varied in intensity between glacial maxima and minima. This colder water was entrained and mixed with a strengthening and expansion of a warmer deep-sea water mass during the early Miocene. Weakened proto-AABW and expanded warmer deep-water, along with stratigraphic evidence of a fully developed EAIS, are consistent with recent ocean and climate numerical model simulations, which suggest that with a fully deepened Drake Passage there would be reduced production of high latitude Southern Ocean deep water and increased warmer more saline deep water originating from the north Atlantic Ocean. This well supported scenario requires a reevaluation of the view that Antarctic ice volume was significantly reduced for most of the early Miocene. Previous estimates have been constrained by the lack of deep water isotopic records proximal to Antarctica, and unduly influenced by the expansion of warmer deep water into most of the ocean basins at this time.

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