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Threshold behavior of a marine-based sector of the East Antarctic Ice Sheet in response to early Pliocene ocean warming

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Abstract We investigate the stability of the East Antarctic Ice Sheet (EAIS) on the Wilkes Land continental margin, Antarctica, utilizing a high-resolution record of ice-rafted debris (IRD) mass accumulation rates (MAR) from Integrated Ocean Drilling Program Site U1359. The relationship between orbital variations in the IRD record and climate drivers was evaluated to capture changes in the dynamics of a marine-based ice sheet in response to early Pliocene warming. Three IRD MAR excursions were observed and confirmed via scanning electron microscope microtextural analysis of sand grains. Time series analysis of the IRD MAR reveals obliquity-paced expansions of the ice sheet to the outer shelf prior to ~4.6 Ma. A decline in the obliquity and a transition into a dominant precession response of IRD MAR occur at ~4.6 Ma along with a decline in the amplitude of IRD MAR maxima to low background levels between ~4.0 and ~3.5 Ma. We speculate that as sea surface temperatures began to peak above 3°C during the early Pliocene climatic optimum, the ice shelves thinned, leading to a greater susceptibility to precession-forced summer insolation and the onset of persistent retreat of a marine-based portion of the EAIS.

1. Introduction

In evaluating the cryosphere and its response to changes in climate, the Pliocene epoch (5.33–2.58 Ma) is considered of great importance due to similar to present oceanographic settings [Haug et al., 2001; Jansen et al., 2007] and carbon dioxide concentrations ranging from ~300 to 415 ppm [Bartoli et al., 2011; Pagani et al., 2010; Seki et al., 2010]. Pliocene warmth can be attributed to the high CO₂ levels [Crowley, 1996]. Compared to today, the high-latitude Southern Hemisphere was warmer and global temperatures were 3–3.5°C above present [Andersson et al., 2002; Fedorov et al., 2013; Raymo et al., 1996].

A global compilation shows that sea surface temperatures (SSTs) were the highest during the early Pliocene climatic optimum, ~ 4.4 Ma [Fedorov et al., 2013]. Early Pliocene sea surface temperatures (SSTs) in the Southern Ocean varied between 2° and 5.7°C [Whitehead and Bohaty, 2003; Escutia et al., 2009; McKay et al., 2012] and may have influenced ice sheet dynamics [Passchier, 2011]. Early Pliocene ice-rafted detritus, however, has been found at lower latitudes, despite sea surface warming [Kennett and Hodell, 1993].

A strong obliquity cycle appears to be present in high-latitude Southern Hemisphere ice volume and climate records [Grützner et al., 2005; Naish et al., 2009; Paul et al., 2000; Zachos et al., 2001]. Summer insolation in the high latitudes is dominated by the precession period, whereas obliquity controls mechanisms of meridional heat and moisture transport [Raymo and Nisancioglu, 2003]. Astronomical forcing of surface temperatures can vary in intensity throughout geologic time, and other features may distort, dampen, or reinforce the astronomical signal [de Boer and Smith, 1994]. For example, by the end of the Miocene, a reorganization of the oceanic gateways may have caused a major shift within the Earth’s climate system and its response to orbital forcing [Paul et al., 2000].

The Integrated Ocean Drilling Program (IODP) drilled seven sites within the Wilkes Land continental margin in order to provide a long-term sedimentary archive encompassing Cenozoic glaciations and their relationship to global climate and oceanographic change [ Expedition 318 Scientists, 2011]. The portion of the East Antarctic Ice Sheet (EAIS) that drains through the Wilkes subglacial basin is grounded mainly below sea level. This segment of the EAIS is considered less stable than other areas of the EAIS and more susceptible to climate change [Cook et al., 2013; Escutia et al., 2005; Orejola et al., 2014]. Currently,
Antarctic ice shelves are thinning as a result of encroachment of circumpolar deep water (CDW) onto the continental shelves. This effect on ice shelves is amplified in glacial drainage systems that are grounded below sea level, where glacial ice is most susceptible to changes in the marine environment [Rignot et al., 2013].

IODP Site U1359 (Figure 1) is located on the Wilkes Land continental rise at 4003 meters below sea level (mbsl), within 100 km off the shelf edge [Expedition 318 Scientists, 2011]. In order to assess the extent of the Earth's polar climate sensitivity and the stability of the EAIS during the Pliocene climatic optimum, we present a high-resolution record of ice-rafted debris mass accumulation rates (IRD MAR) at Site U1359. Through microtextural analysis of the sand fraction (>63–2000 μm), we establish that IRD MAR is glacially derived material transported to the continental rise.

In order for icebergs to be generated, ice sheets must extend toward the continental margins, and surface waters must be cold enough that calving icebergs can survive transport and deposit detritus in the deep ocean [Hemming et al., 2002]. The ultimate volume of sediment deposited depends on the size and numbers of icebergs released and can vary with climatic and glacial regime [Powell and Domack, 1995]. Ice sheets behave like a dynamical system—as climate forcings change over time so do their states of equilibrium [Abe-Ouchi et al., 2013]. Cores in ice-proximal continental margin settings typically capture the complete record of ice sheet dynamics on the adjacent continental shelf [Rashid et al., 2012], whereas distal cores are more strongly influenced by changes in currents and SSTs and thus capture a regional climate signal only partially influenced by ice dynamics [Murphy et al., 2002]. Using a high-resolution IRD MAR record from an ice-proximal site, the relationships between iceberg calving and climate drivers are assessed on orbital time scales. A record of ice rafting by Patterson et al. [2014] from a nearby drill hole extends from 2.2 to 4.3 Ma across a condensed interval at ~3.3–3.5 Ma. Relatively continuous sedimentation between ~5.1 and 3.6 Ma at Site U1359 allows us to capture the full extent of the Pliocene climatic optimum including the response of the East Antarctic Ice Sheet at the onset of peak warming ~4.4 Ma.

2. Materials and Methods

2.1. Study Site

Holes U1359A, U1359B, and U1359C were drilled to total depths of 193.5, 252.0, and 168.7 meters below seafloor (mbsf), respectively. The stratigraphy of the early Pliocene interval is characterized by cyclical variations of three sedimentary facies: (a) bioturbated or weakly laminated light greenish gray diatom-rich silty clays and oozes with dispersed clasts; (b) massive olive gray silty clay with dispersed clasts; and (c) laminated olive gray silty clay with millimeter-to-centimeter-scale silt and fine sand laminae and dispersed clasts [Expedition 318 Scientists, 2011]. This facies assemblage is consistent with the seismic interpretation of channel levee systems [Escutia et al., 2005], and the individual facies are indicative of variable degrees of surface productivity (higher in facies a) and terrigenous supply (higher in facies b), and distal muddy turbidite deposition (facies c). Deposition of all three facies was associated with intermittent deposition of gravel-sized (>2 mm) ice-rafted debris, even within intervals of muddy turbidite laminae. Facies A and B also contained sediment silt and sand clots or clasts, similar to sediment pellets described from other ice-rafted sediments [Goldschmidt et al., 1992].
2.2. Age Model

Age tie points were generated through magneto-biostratigraphic correlation [Tauxe et al., 2012]. All ages are based on Gradstein et al.’s [2004] age scale. Holes U1359A, U1359B, and U1359C were correlated shipboard using the natural gamma radiation and magnetic susceptibility measurements to generate a meter composite depth (mcd) scale [Expedition 318 Scientists, 2011]. The correlation is most accurate in sections with high recovery because natural gamma ray and magnetic susceptibility signatures of thicker stratigraphic units can be matched. Age data in core intervals with significant recovery gaps were omitted from the age model as a consequence of uncertainty in the stratigraphic correlation between the holes. Our sampling targeted the well-recovered early Pliocene interval at ~67–139 mcd in holes U1359A and U1359B. Fifteen age tie points across Holes U1359A, U1359B, and U1359C generate a constant linear sedimentation rate of approximately 45 m/Myr for the interval between ~69 and ~212 mcd (Table 1 and Figure S1 in the supporting information). To account for a condensed interval in the uppermost part of the studied interval (between 68.84 and 69.94 mcd), a stepwise regression model was generated for that section using age tie points from Hole U1359A (Table 1 and Figure S1 in the supporting information).

2.3. Biogenic Opal

The biogenic opal contents at Site U1359 were generated using 74 samples selected from cores 9H (68.92 mcd) to 15H (138.81 mcd) in Hole U1359A. The biogenic silica content was measured using a wet alkaline extraction method modified from DeMaster [1981] and Müller and Schneide, [1993] at Pusan National University. Approximately 10 mg of sample was transferred into a 50 mL polypropylene tube. About 30 mL of a 1N NaOH solution was added to the tubes, which were then closed and placed in a drying oven at 85°C for 5 h. The tubes were vigorously shaken to resuspend the solids at every hour; before 0.10 mL, solution was taken into a 10 mL vial containing 2 mL 0.10N HCl. Dissolved silica was measured using a molybdate blue spectrophotometric method. The analytical precision of standard samples as a relative standard deviation (±1σ) is ±1%. The biogenic opal content was calculated by multiplying biogenic silica content by 2.40 [Mortlock and Froelich, 1989].

2.4. Ice-Rafted Debris

A high-resolution record for the early Pliocene was generated using 348 samples from Hole U1359A and 143 samples from Hole U1359B, spanning a total depth of 67.17–139.15 mcd. Each sample was measured on a dual light source Malvern Mastersizer 2000 laser particle sizer at Montclair State University, which can determine grain size distributions ranging from 0.020 to 2000 μm. Instrument settings followed the recommendations of Sperazza et al. [2004]. All samples were pretreated to remove the biogenic component, and to preserve the terrigenous silicate fraction, by using the methodology employed by Konert and Vandenberghhe [1997]. Following Krissek [1995], IRD MAR values were determined using the bulk particle size distribution based on the equation:

\[ \text{IRD MAR} = \frac{\text{IRD} \times \text{TERR} \times \text{DBD} \times \text{LSR}}{\text{IRD} \times \text{TERR} \times \text{DBD} \times \text{LSR}} \]

where IRD is defined as the volume percent of the terrigenous coarse fraction (>125 μm) derived from laser particle size measurements divided by 100, and the terrigenous fraction is defined as 1-biogenic silica.

<table>
<thead>
<tr>
<th>Hole</th>
<th>Average Depth (mcd)</th>
<th>Depth Error (m)</th>
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<td>2.5810</td>
<td>61.52</td>
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<td>0.02</td>
<td>6.7330</td>
<td>201.53</td>
</tr>
</tbody>
</table>

a Ages are based on the magneto-biostratigraphy from Tauxe et al. [2012]; Depth error listed in Expedition 318 Scientists [2011].

b Meters composite depth.
fraction-carbonate fraction. The biogenic silica fraction was interpolated from the opal data set of U1359A. The carbonate fraction was determined to be negligible (<0.9%) by Expedition 318 Scientists [2011], and no corrections were made. The dry bulk density is derived from shipboard measurements [Expedition 318 Scientists, 2011], and the linear sedimentation rate is calculated using the age model we developed for Site U1359.

A peak in IRD MAR is expected to coincide with poor sorting of the fine fraction indicative of a supply of poorly sorted glacial debris. Sorting of the fine fraction (<125 μm) was calculated using the program GRADISTAT [Blott and Pye, 2001] following the scheme of Folk and Ward [1957], where values are derived based on the lognormal distribution of phi size values. Poorly sorted values are those greater than 1.00, while moderate to well-sorted values are less than 1.00 [Blott and Pye, 2001]. The sorting parameter does not require a correction for biogenic material or sedimentation rates because it is based on the terrigenous particle size distribution [Passchier, 2011].

2.5. Microtextural Analysis

Samples were prepared by sieving through a 63 μm screen, with grains selected at random through a microscope before being mounted onto an aluminum stub. Each sample contained 40 grains. All samples were gold coated and viewed on the Hitachi S-3400N scanning electron microscope (SEM) at Montclair State University using a 12 kV accelerating voltage. Additionally, each grain was assessed for its mineralogy through the use of the Bruker energy dispersive X-ray spectrometer (EDX) to verify that all grains selected were quartz. Samples were then interpreted using a classification scheme derived from Antarctic sediments with six different grain types that are representative of different sedimentary and diageneric regimes [Damiani et al., 2006]. Type 1 grains are characterized as having abundant mechanical breakage features such as conchoidal fractures, arc/straight steps, and fractured plates with absent to very moderate chemical alterations (i.e., solution pits and silica precipitation). Type 2 and Type 3 grains show varying degrees of chemical alteration mixed with mechanical features with Type 2 still preserving the majority of the visible mechanical features and mostly angular to subangular outline. In the case of Type 3 grains, the mechanical features are nearly or completely obliterated by a thick coat of silica precipitation but still retain a subangular to subrounded outline. Abundances of grain types within these higher peaks are used to evaluate the sediment transport histories, in particular the degree of abrasion by eolian and aquatic sediment transport processes, of these glacially sourced grains.

2.6. Time Series Analysis

Time series analysis was performed on the stratigraphically continuous section dated between ~5.1 and 3.6 Ma (70–139 mcd) and excluded the condensed interval. The age model for this section is based on a linear regression with $r^2 = 0.99$ through eleven age tie points in Hole U1359B (Table 1 and Figure S1 in the supporting information), and the regression line also provides an excellent fit through age tie points in Holes U1359A and U1359C (Figure S1 in the supporting information). Time series analysis was conducted using continuous wavelet transform, which allows a data series to be studied at both low and high frequencies simultaneously. Wavelet analysis identifies periodicities that are not stationary, i.e., they can change in amplitude or frequency over time [Torrence and Compo, 1998]. The analysis requires evenly spaced data. However, when the data were interpolated from ~5.1 to 3.6 Ma (generating an average sampling spacing of 3180 years), there was little difference in the results compared to the same analysis with the original, slightly unevenly spaced record. Thus, the interpolated record was used for wavelet analysis. All analyses were performed within the PAleontological STatistics Software ver. 2.17 [Hammer et al., 2001]. Wavelet analysis was done using the Morlet basis function, and responses with Milankovitch periodicities were extracted using band pass filters, where precession was filtered at 19–23 kyr, obliquity at 37–43 kyr, and eccentricity at 98–125 kyr. The 95% confidence contours in the wavelet plots were derived using chi-square distribution [Torrence and Compo, 1998].

3. Results

3.1. Biogenic Opal

Biogenic opal contents of the sediment range from ~3 to 43 wt % (Figure 2). Prominent opal maxima occur between 86 and 87 mbsf-A, 101 and 104 mbsf-A, and 107 and 110 mbsf-A. The downcore distribution of opal
is in reasonable agreement with the shipboard lithological and smearslide observations as recorded on the Visual Core Description sheets [Expedition 318 Scientists, 2011]. Core intervals with numerous millimeter-scale silt and sand laminae coincide with lower opal percentages.

3.2. Particle Size Distributions and IRD MAR

To allow comparison with the detailed lithology log of Hole U1359A (modified from Visual Core Description sheets [Expedition 318 Scientists, 2011]), IRD data from Holes U1359A and U1359B were plotted on the U1359A depth scale by converting from mcd to meters below seafloor (mbsf-A). Within the U1359 record are three distinct intervals of high amplitude and highly variable IRD MAR, which we designate as IRD MAR excursions I, II, and III (Figures 2 and 3a). The most prominent IRD MAR maxima can be identified at depths 123–126 mbsf-A (excursion I), 111–119 mbsf-A (excursion II), and 86–94 mbsf-A (excursion III) and generally have values of ~2 g/cm²/kyr or higher, while smaller, intermittent peaks tend to be ~1 g/cm²/kyr or less. Stratigraphically below each IRD MAR maximum is an interval of very low, intermittent IRD MAR followed by an abrupt upward increase and then gradual decrease. These sharp-based IRD maxima are marked by very poor sorting of the fine fraction (< 125 μm). A steady leveling off of IRD MAR occurs between 67 and 87 mbsf-A.

Overall, the shipboard lithological observations are in agreement with the general trends of silt and clay with lower amounts of clay in the diatomaceous facies than in silty clay with dispersed clasts facies. The diatom-rich silty clay facies coincides with sections of higher terrigenous silt and lower clay percentages. In contrast, the grey clay facies coincides with a relatively high clay percentage with the exception of one IRD MAR peak (~113 mbsf-A).

3.3. Quartz Grain Surface Textures

Based on observations of the calculated IRD MAR, a total of seven samples were selected in order to assess sand grain shapes and surface microtextures (Figure 3a). Large peaks in IRD (> 1 g/cm²/kyr) were the main focus in order to determine the amount of iceberg rafted (i.e., glacially derived) material. The grain...
outlines ranged from angular to subrounded and show numerous mechanical breakage features with absent to moderate chemical alterations. As a whole, the samples show a similarity between them with dominance in glacial Types 1–3 grains (Figure 3b) [Damiani et al., 2006]. It should be noted that the samples within IRD MAR excursion I are from a section of less variable, persistently high IRD MAR, where the peaks are very closely spaced. Samples from this lower interval show a dominance in Type 1 grains (Figure 3c, top). The samples within the upper intervals are from a more variable part of the IRD MAR record and show higher proportions of grain Types 2 and 3 (Figure 3c, middle and bottom, respectively).

3.4. Time Series Analysis

Wavelet analysis found precession, obliquity, and eccentricity cycles at varying intensities throughout the record (Figure 4a). The presence of two lower wavelet frequencies that equate to ~467,000 and ~268,000 years decrease in intensity and span only a few complete cycles (Figure 4a). These lower frequencies could be the result of a convolution of the other cycles found within the record or nonorbital influences on ice dynamics. When the data were detrended using the log10 centered on 0, lower frequencies such as obliquity were enhanced (Figure 4b), particularly between 4.3 and 3.9 Ma. When compared to summer insolation forcing (at 65°S) (Figure 4c) [Laskar et al., 2004], obliquity does not have a strong presence. The band-pass filtered record initially shows a dominant response in the obliquity band (Figure 5c), with a transition to a dominant response in the precession band at ~4.6 Ma (Figure 5b). IRD MAR maxima coincide with eccentricity minima at ~4.9 and 4.2–4.0 Ma (Figure 5e).

4. Discussion

4.1. Sedimentation at Site U1359

The sedimentology of the intervals with IRD MAR maxima changes from excursion I (~4.9–4.8 Ma) with respect to excursions II and III (4.7–4.5 and 4.2–4.0 Ma, respectively) in U1359 (Figure 2). The high peaks of IRD MAR within excursion I occur within sections of laminated millimeter-scale silty sand with dispersed
clasts. In contrast, the intervals encompassing excursions II and III are not positioned in laminated sections and contain more abundant silt- to sand-sized sedimentary aggregates and higher opal contents [Expedition 318 Scientists, 2011]. Unmodified Type 1 glacial microtextures are also more abundant in excursion I (Figure 3) with respect to excursions II and III.

The sedimentary facies with very low opal contents and high mass accumulation rates of IRD (>2 g/cm²/kyr) within excursion I (~4.9–4.8 Ma) are consistent with ice sheet advance to the shelf edge. The greater abundance of Type 1 grains within excursion I indicates continuous deposition from a glacial source with little influence from current-controlled sedimentation. This IRD maximum occurs within graded laminated mud facies, which can be explained by a combination of iceberg rafting and sediment lofting from hyperpycnal flows under increased meltwater discharge of an ice sheet grounded on the outer shelf [Hesse and Khodabakhsh, 2006; Rashid et al., 2003]. This interpretation is corroborated by the presence of early Pliocene ice-proximal diamictons older than 3.99 Ma [5.12–4.40 Ma; Iwai, personal communication, 2013] at

Figure 4. Morlet-powered wavelet spectrum of Site U1359 (a) evenly spaced IRD MAR, (b) detrended (log10) IRD MAR, and (c) mean monthly summer insolation at 65°S [Laskar et al., 2004], highlighting orbital signal intensities over time. The 95% confidence contour was derived using chi-square distribution [Torrence and Compo, 1998].
Site U1358 on the adjacent continental shelf [Orejola et al., 2014]. In the Southern Ocean, extensive Pliocene-Pleistocene ice rafting events occur during glacial/cold stages at the onset of deglaciations when ice sheets are still large and grounded on the continental shelves [Murphy et al., 2002; Passchier, 2011; Weber et al., 2014].

In contrast to modern day, a high amount of far traveled ice-rafted debris with a Wilkes Land and Adélie Land source was deposited during this time at Site 1165 [Williams et al., 2010].

The onset of ice retreat from the shelf at ~4.7 Ma can be denoted by a spike in the gravel fraction and high IRD MAR followed by diminution (Figure 2). Under warming, but still relatively cold SSTs, gravelly muds are typically deposited during ice shelf breakup [Evans and Pudsey, 2002], followed by hemipelagic sedimentation [Caburlotto et al., 2010].

Poor sorting and paucity of laminations within IRD rich diatom-bearing sediments of the two upper intervals (excursions II and III; ~4.7–4.5 Ma and ~4.2–4.0 Ma, respectively) indicates deposition due to terrigenous fall out from sediment plumes and/or iceberg rafting [Caburlotto et al., 2010]. High opal contents are indicative of interglacial periods with reduced sea ice coverage and warm climatic conditions when ocean heat transport exerts a maximum influence in the Southern Ocean [Whitehead and Bohaty, 2003; Grützner et al., 2005; Escutia et al., 2009; McKay et al., 2012].

SEM analysis of grains out of excursions II and III shows higher proportions of grain Types 2 and 3 (Figure 3b), indicating some abrasion and chemical alteration of glacially derived grains. An increase in the chemical alteration of grain surfaces may suggest a sea ice-rafted debris origin for those grains as discussed in St. John et al. [2015]. SSTs at the time of excursions II and III were highly variable and ranged between 1 and 5°C (Table 2 and Figure 5a). Alternatively, the scarcity of “fresh” glacial grains within the upper intervals II and III as well as the presence of common sand and silt aggregates dispersed within the mud fraction [Expedition 318 Scientists, 2011] may be explained by the overdeepening of the Wilkes basin. Glaciohydraulic supercooling, a process that occurs when a glacier flows through an overdeepening, is associated with periods of high water flux and ice accretion (frazil ice) in response to hydraulically

**Figure 5.** (a) Early Pliocene sea surface temperatures based on values compiled in Table 2 [McKay et al., 2012; Whitehead and Bohaty, 2003; Escutia et al., 2009]. Site U1359 IRD MAR band-pass filtered periodicities of (b) precession, (c) obliquity and (d) eccentricity with (e) Laskar et al. (2004) eccentricity cycle (400 kyr and 100 kyr), and (f) IRD MAR.
Table 2. Early Pliocene Sea Surface Temperatures¹

<table>
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<th>Chron</th>
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<th>SST Range (°C)</th>
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</thead>
<tbody>
<tr>
<td>C2An.3n</td>
<td>3.330–3.596</td>
<td>1–5</td>
</tr>
<tr>
<td>C2Ar</td>
<td>3.596–4.187</td>
<td>1.5–5.7</td>
</tr>
<tr>
<td>C3n.1n</td>
<td>4.187–4.300</td>
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<tr>
<td>C3n.4n</td>
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</table>

¹Early Pliocene East Antarctic SSTs compiled from McKay et al. [2012], Whitehead and Bohaty [2003], and Escutia et al. [2009].

regulated temperature and pressure changes [Lawson et al., 1998]. The presence of supercooled meltwater may have encouraged the accretion of chemically altered glacial grains. The formation and suspension of sand and silt as aggregates may also have resulted from the growth of frazil ice on sediment particles and subsequent rapid entrainment into the growing basal ice. After incorporation into sea ice or glacial ice, the consolidated aggregates can melt out after ice rafting and survive a drop of several kilometers through the water column retaining their integrity even after burial [Goldschmidt et al., 1992].

4.2. Iceberg Calving Mechanisms and Climate Forcings

IRD MAR excursion I coincides with a 400 kyr eccentricity minimum [Laskar et al., 2004] and shows a strong obliquity response in the IRD record of Site U1359 (Figures 4a and 5). This is in agreement with other records: (1) Miocene stable isotope data that predate the onset of significant Northern Hemisphere glaciation also show Antarctic ice sheet growth during 400 kyr eccentricity minima [Liebrand et al., 2011]; (2) Obliquity-paced Antarctic sedimentation records are known from Ocean Drilling Program (ODP) Site 1165 (Prydz Bay) and AND-1B (Ross Sea) for the same period of ~5.2–4.6 Ma [Grützner et al., 2005; Naish et al., 2009]. During ice advances to the shelf break in chron C3n.3n (4.99–4.79 Ma), which encompasses IRD MAR excursion I, SSTs were relatively consistent between 2 and 3°C (Table 2 and Figure 5a). To allow for ice sheet advances to the shelf break under these relatively warm SST conditions, high snow accumulation is necessary to maintain a positive ice sheet mass balance, perhaps similar to the “snow-gun hypothesis” [Prentice and Matthews, 1991], which has also been put forward to explain Miocene Antarctic ice growth under warm SST conditions [Shevenell et al., 2008].

Obliquity controls the ice sheet surface mass balance through its effect on meridional moisture transport. During times of reduced summer insolation, snow and ice can persist and survive through the meltback season [Raymo and Nisancioglu, 2003]. The increased snow accumulation from year to year would eventually lead to full glacial conditions paced by obliquity cycles. Moreover, early in the Pliocene, the summer insolation at 65°S was paced by obliquity, with weaker precession due to low eccentricity [Laskar et al., 2004] (Figure 4c). These variables explain the obliquity-paced discharge of glacially derived material from the Wilkes Land margin between ~5.1 and 4.6 Ma.

The onset of ice retreat in chron C3n.2r (4.79–4.63 Ma), coincident with IRD MAR excursion II, shows a combined precession, obliquity, and 100 kyr eccentricity response (Figures 4a and 5) and marks a transition from a dominant obliquity to precession response of iceberg discharge at ~ 4.6 Ma. Summer insolation at 65°S from ~4.6 Ma onward is controlled by precession [Laskar et al., 2004] (Figure 4c), and variability in ice shelf surface melt [Hulbe et al., 2004] could account for a change in iceberg discharge. In excursion II, IRD MAR are low (<2 g/cm²/kyr) and variable during the latter half of this transition and suggest that the ice sheet was no longer building up in mass similar to the excursion I scenario. As a feedback, ice retreat may have periodically allowed incursion of relatively warm CDW onto the Wilkes Land continental shelf with basal melt enhancing ice retreat. Higher IRD MAR peaks within excursions II and III signify the survival of the ice shelves under gradual warming. Weakening of an ice shelf through subsurface warming has also been a recent conjecture to explain iceberg discharge [Alvarez-Solas et al., 2010; Marcott et al., 2011].

Ocean temperature likely played an important role in controlling the long-term marginal fluctuations of ice sheets [Joughin et al., 2012]. A broader range of SSTs is reconstructed around East Antarctica between ~4.5 and 3.6 Ma (Table 2 and Figure 5a), including abrupt warming events to 5.7°C documented during C2Ar (4.18–3.59 Ma) [Whitehead and Bohaty, 2003; Escutia et al., 2009]. These rapid ocean warming events may have caused the marine-based ice to thin and retreat substantially as a result of subsurface melt. In
agreement with our findings, a modeling study targeting the Wilkes subglacial basin indicates that although warming of any kind likely forces the ice sheet to retreat, the marine-based ice might be particularly susceptible to fast changes in ocean heat supply [Mengel and Levermann, 2014], as observed for the Southern Ocean between ~4.5 and 3.6 Ma. IRD MAR declines to low background levels between ~4.0 and 3.6 Ma, indicative of a greater role of basal melt rather than iceberg discharge. Modeling studies show that rapid ice retreat occurs through basal melt rather than calving under high SSTs so that IRD MAR is expected to be minimal under full interglacial conditions [Rignot et al., 2013; Joughin et al., 2014; Mengel and Levermann, 2014].

We speculate that a major regime change from a large, obliquity-paced marine-based ice sheet to a smaller, precession-paced ice sheet may have occurred around 4.6 Ma. A larger ice sheet persisted with SSTs of 2–3°C. When SSTs began to warm, ice volume initially increased due to the snow gun effect. The ice sheet-ocean system, however, exhibited threshold behavior as SSTs peaked above 3°C and tipped the balance of accumulation and ablation in favor of the latter. Continued warming initiated a system change where the marine-based ice thinned and became more susceptible to high-latitude insolation forcing.

The timing of the transition from an obliquity-paced to a precession-paced ice sheet at ~4.6 Ma contrasts with a recent study by Patterson et al. [2014] at nearby Site U1361, who argued for a change in the periodicity of ice dynamics between 3.3 and 3.5 Ma. This change coincides with a condensed interval in that record [Patterson et al., 2014, Figure S5 in their supporting information]. At Site U1361, an obliquity signal is expressed when analyzing a short interval of low-amplitude IBRD MAR between 4.0 and 3.5 Ma [Patterson et al., 2014, Figure 3a] (Figure S4b in the supporting information). The main difference with our initial approach is that Patterson et al. [2014] (1) isolated short segments and detrended their record before time series analysis and (2) tuned their age model using the IBRD MAR data set and then interpreted this signal as ice dynamics. However, even without detrending and in the untuned record, the obliquity signal is expressed below the condensed interval dated between 4.0 and 3.5 Ma [Patterson et al., 2014, Figure 3a] (Figure S3 in the supporting information). The tuning of the age model further diminished the higher frequency signal and accentuated the response in the obliquity band [Patterson et al., 2014, Figure 4b] (Figure S4 in the supporting information). Our detrended record (Figure 4b) also shows an obliquity signal between 4.3 and 3.9 Ma.

For the interval of 4.0–3.5 Ma, however, our IRD MAR values at Site U1359 are very low (Figure Sf and Figure S2 in the supporting information), and the absolute values of IBRD MAR at Site U1361 do not exceed 0.2 g/cm²/kyr [Patterson et al., 2014] (Figure S2 in the supporting information, this study). Values this low are more typical of distant ice rafting events involving far-traveled icebergs [e.g., Kennett and Hodell, 1993]. The interpretation of such low signals of long-distance ice rafting is complicated by the influence of SST and currents on iceberg survival rates and routing and may not accurately depict ice dynamics.

In contrast to Patterson et al. [2014], we do not interpret the low-amplitude obliquity cycles in the interval between 4.0 and 3.6 Ma as an expression of the dynamics of the East Antarctic Ice Sheet. We argue that only the larger amplitude variations in IRD MAR carry that signal (Figure 5). At Site U1359, we analyzed the periodicities of the complete IRD MAR record, through the early Pliocene (5.1–3.6 Ma), which provides evidence of larger ice rafting events that are likely more locally sourced from the Wilkes Subglacial Basin. Our ice rafting events broadly correlate to interpretations of ice dynamics by Cook et al. [2013] based on a low-resolution 14C record for Site U1361 (Figure S2 in the supporting information). Based on our analysis of a record of IRD MAR events, we argue for a change from an obliquity to precession-paced marine-based East Antarctic Ice Sheet at ~4.6 Ma.

The shift in early Pliocene ice dynamics around ~4.6 Ma coincides with major changes in ocean circulation. The closing of the Central American Seaway between 4.7 and 4.2 Ma gradually altered the transport of heat [Haug et al., 2001; Haug and Tiedemann, 1998; Steph et al., 2010], concurrent with warming in the Southern Ocean [Whitehead and Bohaty, 2003; Escutia et al., 2009]. The LR04 benthic stack also shows a shift toward coherency with precession starting ~4.5 Ma, which becomes significant at ~4.1–2.8 Ma, and is attributed to Northern Hemisphere glaciation or northern deepwater formation [Lisiecki and Raymo, 2005]. On the other hand, an Earth System modeling study with mid-Pliocene boundary conditions [Zhang et al., 2013] challenges a North Atlantic origin of deepwater formation. Under reduced Pliocene ice sheet boundary conditions, the model simulates a poleward migration of the westerlies, reduced ocean
stratification, and no sea ice but deepwater formation in the Southern Ocean [Zhang et al., 2013]. In the context of this modeling study, the precession-paced ice discharges ~4.6–4.0 Ma provide an alternate interpretation for the increased coherency with precession in the deep-sea isotope data ~4.5 Ma [Lisiecki and Raymo, 2005]. A southern source of precession-driven deepwater formation is in line with other emerging evidence of feedbacks involving EAIS dynamics and ocean circulation [Goldner et al., 2014; Woodard et al., 2014].

5. Conclusions

We acquired high-resolution ice-rafted debris mass accumulation rates (IRD MAR), SEM surface texture data, and opal weight percent to assess marine ice sheet dynamics in the Wilkes basin during the early Pliocene. Three major iceberg rafting episodes were recognized which show a significant evolution in ice dynamics from the early Pliocene into the mid-Pliocene:

1. Excursion I (4.9–4.8 Ma) is characterized by the laminated, graded mud facies with high IRD MAR (>2 g/cm²/kyr) indicative of ice sheet expansion to the outer shelf. Intense iceberg discharge episodes were accompanied by increased meltwater discharge during an insolation minimum and relatively warm SSTs (2–3°C).

2. Excursions II/III (~4.7–4.5 Ma and ~4.2–4.0 Ma, respectively) have lower amounts of IRD MAR (<2 g/cm²/kyr) and a paucity of laminations and fresh glacial textures of a more retreated ice margin. Along with a transition in sedimentological properties at ~4.6 Ma, the filtered IRD MAR record shows a shift from an obliquity to a precession influence concurrent with an intermittent rise in SSTs in the Southern Ocean above 3°C.

Based on the sedimentological records, we speculate that during this transition at ~4.6 Ma, basal melt led to thinning of the ice sheet margin and variability in ice shelf surface melt due to a larger influence of high-latitude insolation. The implication is that a larger marine-based ice sheet can be maintained in the Wilkes Basin with SSTs up to 2–3°C. However, once SSTs periodically rise above 3°C, continued warming may have caused the ice sheet to become more susceptible to high-latitude warming, in agreement with previous modeling studies [Mengel and Levermann, 2014].

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