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Antarctic ice sheet-ocean connections enhance Earth system sensitivity to obliquity forcing

Levy, R.H., Meyers, S.R., Naish, T.R., Golledge, N.R., McKay, R.M., Crampton, J.S., DeConto, R.M., De Santis, L., Florindo, F., Gasson, E.G.W., Harwood, D.M, Luyendyk, B.P., Powell, R.D., Clowes, C., and Kulhanek, D.

Antarctic ice sheet (AIS) growth and decay is strongly influenced by astronomical variations, yet it is not known why AIS response to this climate driver varies through time. Here we examine AIS variability from 34 to 5 million years ago through integration of geological records from the Antarctic margin and a novel assessment of sensitivity to changes in Earth's axial tilt (obliquity sensitivity) derived from the oceanic oxygen-isotope proxy for global ice volume. Three phases of AIS development are found: (1) ~34-24 Ma – a largely terrestrial ice sheet with low obliquity sensitivity; (2) 24 to 14 Ma – frequent ephemeral marine ice sheets with amplified obliquity sensitivity; and (3) 14 to 5 Ma - episodes of extensive marine ice sheet advance, persistent sea ice, and a general decrease in obliquity sensitivity. These phases are associated with decreasing atmospheric CO₂ and progressively colder mean climate states. Our analysis suggests the AIS is most sensitive to obliquity forcing when it extends into marine environments and sea-ice extent is limited. We infer this is due to obliquity-driven changes in meridional temperature gradient that affect the position and strength of circum-Antarctic easterly flow, which enhances (or reduces) ocean heat transport across the Antarctic continental margin.

Insight into causes of Antarctic ice sheet variability – over a range of time scales – is fundamental to our understanding of Earth system response to climate change. Large scale shifts in AIS volume and extent are controlled by changes in atmospheric CO₂^{1,2} and plate

tectonic processes³ and usually occur over extended periods of time (hundreds of thousands to several million years). Geological snap-shots from the Antarctic margin show that higher frequency oscillations in the AIS (glacial-interglacial episodes) have been paced by astronomical variations in insolation involving eccentricity^{4,5} (orbital shape, ~400 and 100 kyr), obliquity⁶ (axial tilt, 41 kyr), and precession⁴ (wobble of Earth's axis, ~20 kyr) cycles. Near-continuous records of ice volume variation captured in oxygen isotope records ($\delta^{18}\text{O}$) from deep ocean sediment cores⁷⁻¹⁰ show that the frequency of glacial-interglacial variability has evolved over the past 34 million years (Fig. 1a). For example, glacial cycles during the Oligocene through early Miocene were primarily paced by changes in long and short period eccentricity^{8,9} whereas the influence of obliquity increased during the mid-Miocene climate transition¹⁰ and became dominant in the late Miocene. These observations of variable ice sheet response from both direct records at ice proximal locations and indirect geochemical proxies present a conundrum. It is well-established that changes in Earth's astronomical configuration affect insolation in a predictable manner¹¹ so why was the AIS was more sensitive to specific astronomical frequencies at different times? Ultimately, this feature suggests key transitions in the behaviour of the AIS related to ice sheet size and dynamics (e.g., terrestrial vs. marine based ice sheets).

To address this question, we conduct a novel assessment of ice volume and high latitude surface temperature sensitivity to obliquity forcing (Fig. 1), computed from the deep marine $\delta^{18}\text{O}$ proxy record⁷, and integrate this assessment with AIS-proximal geological records from the Antarctic continental shelf, as well as modern observations and modelling studies. As will be demonstrated, *obliquity sensitivity* provides a paleo-sensor for the detection of terrestrial vs. marine-based ice sheets, and thus sheds new light on the evolution of the AIS. To focus exclusively on the AIS, we restrict our analysis on the period from 34 to 5 Ma, since the last five million years of Earth's History is characterised by increasing influence of ice

50 sheets in the northern hemisphere.

51 We calculate *obliquity sensitivity* (S_{obl}) by dividing obliquity variance in a $\delta^{18}\text{O}$ megasplice⁷
52 by the variance of the theoretical obliquity solution¹¹ (see methods). Three distinct episodes
53 in S_{obl} are revealed. Relatively low S_{obl} punctuated by small increases every 2.4 million years
54 characterises the Oligocene. A substantial increase in S_{obl} occurs in the latest Oligocene, and
55 the early to mid-Miocene is characterised by high S_{obl} variation. Maximum S_{obl} was reached
56 during the Miocene Climate Transition (MCT) 13.8 million years ago. Following the MCT,
57 S_{obl} decreased to low baseline values comparable to the Oligocene, but included episodes of
58 moderate S_{obl} . We compare computed S_{obl} with direct evidence of AIS variability from the
59 Antarctic continental shelf (Figs 1 and 2), to examine the influence of ice sheets on S_{obl} . We
60 focus on the Ross Sea (Fig. 2), since well-dated drill cores and seismic profiles across the
61 region provide a composite stratigraphy from the Eocene to Pleistocene linked to glacial
62 processes that help constrain glacial history^{5,6,12-16}. Unfortunately, stratigraphic records from
63 other regions of Antarctica's continental shelf are few and are difficult to precisely date due
64 to discontinuous core recovery¹⁷⁻¹⁹. However, numerical models indicate that ice sheet
65 variability in the Ross Sea reflects large scale changes across the continent (Supplementary
66 Figure 1) and suggest that major environmental shifts captured in geological records from the
67 Ross Sea occur in other regions of Antarctica at the same time.

68 Large continental-scale ice sheets became established on the Antarctic continent across the
69 Eocene-Oligocene Transition^{5,20}. However, expansion into marine settings at the margins of
70 the Ross Sea did not occur until 32.8 Ma, evidenced by an increase in glacimarine sediments
71 in the Cape Roberts Project (CRP) -3 drill core.⁵ This increase coincides with a small peak in
72 S_{obl} (Fig. 1). Subsequent maxima in S_{obl} through the Oligocene occur every 2.4 Myrs and
73 coincide with disconformities in Ross Sea drill cores (Fig. 1; Supplementary Table 1), which

reflect advance of ice beyond the Southern Victoria Land coastal margin. These data suggest that increases in S_{obl} occurred when outlet glaciers advanced beyond their terrestrial margins into marine environments and that the Earth system became more sensitive to obliquity forcing when small regions of the AIS were connected to the ocean. However, most of the Oligocene is characterized by low S_{obl} , and 100 and 400 kyr cycles dominate $\delta^{18}\text{O}$ records⁹ (Fig. 1), which suggests that Antarctica's terrestrial ice sheets were most sensitive to changes in atmospheric temperatures paced by variations in eccentricity and precession, consistent with direct insolation forcing.

A prominent increase in S_{obl} between 24.5 and 24 Ma marks one of the most significant environmental transitions in Antarctica since the Eocene-Oligocene Transition (Fig. 1). The first occurrence of ice proximal glacial marine sediments in Deep Sea Drilling Project Site 270²¹, disconformities in CRP-2/2A²², a large turnover in Southern Ocean phytoplankton (Fig. 1; methods; Supplementary Fig. 2), and seismic data¹³ suggest the first major expansion of marine ice sheets across the Ross Sea continental shelf occurred during this time interval. Proxy data indicate that CO_2 concentrations dropped below 600 ppm in the latest Oligocene and remained below this value through most of the Neogene². We postulate that under 'high' CO_2 climate states prior to 24.5 Ma, only small regions of the AIS could advance into marine settings during cold astronomical configurations; warm seas precluded ice sheet advance across the continental shelf. As CO_2 dropped below 600 ppm, ocean temperatures cooled and the AIS advanced across Antarctica's continental shelves, connecting increasingly larger areas of marine-based ice with the ocean. Maximum AIS extent during this phase of global cooling occurred between 23.2 and 23 Ma and is reflected by maxima in $\delta^{18}\text{O}$ records^{9,23,24}. The coincident increase in S_{obl} suggests that ocean driven oscillations in marine portions of the AIS were more strongly influenced by changes in Earth's axial tilt.

Ice advanced into marine environments across the Ross Sea at 17.9 Ma¹⁵, as shown by a
disconformity at 775 mbsf in the ANDRILL (AND) – 2A drill core that coincides with Ross
Sea seismic unconformity (RSU 4A). Deformed diamictite units overlie this disconformity
and indicate that ice remained grounded near the drill site until 17.4 Ma. Subsequent ice
margin retreat to the coast is reflected by a change to more ice-distal glacial-marine lithofacies
in AND-2A (Figs. 1 and 3). An indirect record of marine ice sheet advance during this
interval is captured in sediments and downhole geophysical data from ODP Site 1165⁴
offshore Prydz Bay (Figs 2 and 3). Most of the early to mid-Miocene record at this site
comprises alternating facies of dark grey to black claystone with silt laminae and rare or
absent ice-rafted-debris (IRD) (Facies 1) and greenish grey bioturbated structureless
claystone with common IRD (Facies 2). Peaks in downhole resistivity logs correlate with
Facies 2⁴. Resistivity data through the interval from ~750 to 500 mbsf includes a section of
high variability (Fig. 3; Supplementary Fig. 3) that records an increase in Facies 2 unit
thickness⁴ and potentially reflects enhanced ice berg and sediment flux to the continental
shelf margin due to more extensive and persistent ocean-ice sheet connections. These two
records indicate marine ice sheet advance occurred around Antarctica between ~18 and 17.4
Ma. These geologic data coincide with an interval of high S_{obl} (Fig. 1 and 3) and offer
additional evidence that S_{obl} is closely linked to the presence (or absence) of extensive marine
ice sheets on Antarctica's continental shelves. Far-field sea level records preserved in
stratigraphic sequences along the New Jersey margin²⁵ record a 10 to 15m fall in relative sea
level between 18 and 17.5 Ma, which supports proximal geologic evidence for an expanded
AIS. This episode of sea level fall follows a period of relatively stable sea level that coincides
with low S_{obl} (Fig. 3). A 20-m rise in sea level approximately coincides with a decrease in
 S_{obl} beginning at 17.4 Ma and is followed by another long interval of stable sea level that
coincides with low S_{obl} (Fig. 3).

S_{obl} increased through the Miocene Climate Transition (MCT), reaching maximum values at ~13.8 Ma coincident with a large 1.5 ‰ shift in $\delta^{18}\text{O}$ (Fig. 1). Disconformities and proximal grounding-zone lithofacies dominate Ross Sea drill core records through this interval^{15,16} (Fig. 2) and erosional unconformities in seismic data indicate that marine ice sheets grounded across the continental shelf. Biological proxies suggest that sea ice became more temporally persistent across the MCT^{15,26,27}. Atmospheric CO₂ concentrations dropped below 300 ppm between 14 and 13 Ma²⁸. The MCT is interpreted to record another CO₂-controlled climatic threshold across which high latitude surface temperatures decreased²⁹ and perennial sea-ice grew around the Antarctic margin for the first time^{15,27}. However, this climatic shift was transient as temperature increases in the late Miocene are reflected by a change from polar to subpolar glacial-marine lithofacies in the AND-1B drill core¹⁶. Despite this climatic rebound, geological records of late Miocene age are missing in drill core disconformities, which suggests that marine-based ice sheets became a more persistent feature after the MCT and repeatedly grounded across the shelf during the late Miocene. We infer that the increases in *S_{obl}* at ~9.5 Ma and ~5.8 Ma reflect episodes of decreased sea ice extent. While *S_{obl}* was variable through the late Miocene, it remained relatively low (compared to the early to mid-Miocene).

Our analysis indicates that the AIS was most sensitive to obliquity forcing when it advanced into marine environments, which suggests ocean dynamics played a role in driving marine ice sheet variability at the 41 kyr frequency. Studies of recent glacial dynamics^{30,31} and ice sheet modelling^{32,33} indicate that ocean dynamics play a significant role in driving marine-based ice sheet retreat. However, analysis of ocean-ice interactions over long glacial-interglacial time scales using detailed physical models are not yet possible. We draw on modern observations and modelling studies of contemporary oceanographic processes across the Antarctic

continental margin^{34,35} to offer a conceptual model to explain how changes in obliquity could influence marine ice sheets (Fig. 3).

Obliquity affects Antarctica's marine ice sheets via its influence on the meridional temperature gradient. As Earth's axial tilt increases, high latitudes warm, meridional temperature gradients decrease, and zonal winds weaken³⁶. Southward migration of southern hemisphere westerly winds (SWW) increases wind stress above the Antarctic Circumpolar Current (ACC) causing it to speed-up³⁷. Ekman transport north of the ACC increases, which enhances upwelling of warm deep water in the southern limb of the over-turning circulation³⁷. At the same time, Antarctic easterlies weaken and migrate southwards, causing isotherms along the Antarctic slope to shoal, thereby promoting advection of warm water into grounding zones and ice shelf cavities³⁴. Decrease in wind shear stress across the Antarctic slope front causes shoaling of isopycnals and enhances eddy driven transport of warm water across the continental shelf margin³⁵. During glacial intervals, these large-scale processes reverse as Earth's tilt decreases and meridional temperature gradients increase. Northward migration and strengthening of zonal winds reduce upwelling of warm water across the shelf. Periods of cold mean climate are characterised by extensive sea ice growth which further reduce the influence of zonal winds across Antarctic slope and continental margin.

Our model identifies three phases of AIS evolution over the period 34-5 Ma (Fig. 4).

Obliquity sensitivity during the early Oligocene was low because the circum-Antarctic Southern Ocean basin was still evolving and Earth's climate state was too warm to support marine ice sheets (Fig. 4a). Variation in local insolation forcing due to 400 and 100 kyr eccentricity modulated precession cycles drove terrestrial ice sheet oscillations. By late Oligocene, circum-Antarctic large-scale circulation patterns that characterise the modern Southern Ocean had been established³⁸. Climatic cooling associated with a drop in atmospheric CO₂ allowed ice sheets to expand beyond their terrestrial margins and ground

across areas of Antarctica's continental shelves. Glacial-interglacial advance and retreat of marine-based portions of the AIS were now influenced by obliquity-paced changes in ocean dynamics across the continental margin. This fundamental shift in AIS dynamics is reflected by an S_{obl} that became higher and more variable from 24 to 14 Ma (Figs. 1, 4b). Water temperatures across the Ross Sea through this period varied between ~ 0 and 10°C ¹⁵ and suggest significant dynamic exchange between the Southern Ocean and Antarctic continental shelves. A general decrease in long and short eccentricity variance in the $\delta^{18}\text{O}$ record, and increase in the obliquity signal, occurs after 13 Ma and persists through much of the late Miocene (Fig. 1). We posit that climatic cooling across the MCT decreased the influence of local insolation on surface melt and reduced the magnitude of terrestrial ice sheet variability, which is reflected by a weakened eccentricity signal in the $\delta^{18}\text{O}$ record (Fig. 1a; Supplementary Figure 4a). Oscillations in AIS volume and extent were now strongly influenced by changes in marine-based ice in East and West Antarctica that were driven by obliquity modulated upwelling of warm water from the circum-Antarctic Southern Ocean (Fig. 4c; Supplementary Figure 4c-e). Episodes of low S_{obl} in the late Miocene reflect times when climate cooled and extensive sea ice developed and created a barrier that reduced oceanic influence on ice sheet variability (Fig. 4c). During these cold episodes, marine ice sheet variability and S_{obl} remained low. In contrast, during intervals when climate warmed enough to melt sea-ice but remained cold enough to maintain small marine ice sheets through interglacial intervals, marine ice sheets remained connected to obliquity driven changes in ocean dynamics and variations in S_{obl} primarily reflect changes in obliquity forcing variance.

If sea-ice cover decreases in the coming decades, our results suggest that enhanced oceanic heat delivery (modulated by present day obliquity forcing) will facilitate ocean-driven melt at the AIS margin. Antarctica's continental shelves now deepen inland, which creates a dynamical instability that enhances marine-ice sheet retreat and volume loss. Our data

support recent ice sheet model simulations^{33,39} and imply stabilization or reduction of atmospheric CO₂ is required to avoid loss of ice shelves and retreat of Antarctica's marine ice sheets.

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Methods

Obliquity Sensitivity. We define $\delta^{18}\text{O}$ obliquity sensitivity (S_{obl}) as:

$$S_{obl} = \frac{\sigma_{\delta^{18}\text{O}}^2}{\sigma_{La04}^2}$$

where $\sigma_{\delta^{18}\text{O}}^2$ is the obliquity variance in the $\delta^{18}\text{O}$ megasplice⁷, in units of permil², and σ_{La04}^2
is the variance of the theoretical obliquity solution¹¹, in units of degrees². Multi-taper method
time-frequency power spectrum integration is utilized to quantify S_{obl} ^{40,41}. To isolate the
dominant 41 kyr obliquity signal, spectrum integration is conducted from 0.023 to 0.027
cycles/kyr (~43.5 to 37 kyr). All time-frequency analyses employ three 2π prolate data tapers,
with a 1-million-year window and a 10 kyr time step; a linear trend is removed from each 1
myr window prior to analysis.

The $\delta^{18}\text{O}$ megasplice is characterized by variable sampling resolution, with a median
resolution of 2.38 kyr. Larger sample spacing through portions of the record could diminish
the obliquity signal strength. To compensate for this, the theoretical obliquity solution¹¹ is
resampled on the temporal grid of the $\delta^{18}\text{O}$ megasplice. Both the megasplice and resampled
obliquity solution are then interpolated using a 2.5 kyr grid (Supplementary Fig. 4c, black
line). A reduction in $\delta^{18}\text{O}$ obliquity strength ($\sigma_{\delta^{18}\text{O}}^2$) due to coarser resolution sampling is

compensated by a reduction in σ_{La04}^2 .

To further evaluate the impact of the megasplice sampling grid on our conclusions, we conduct two additional sensitivity analyses: (1) we evaluate the fraction of the 40 kyr variance that is recovered from the resampled theoretical obliquity solution following application of the megasplice temporal grid, and (2) we compare S_{obl} analyses using both the resampled and unresampled obliquity solution (Supplementary Fig. 4c). These analyses confirm that our assessment of $\sigma_{\delta^{18}O}^2$ and S_{obl} is robust for portions of the record younger than 33.87 Ma, where > 70% of the 40 kyr variance is recovered (91+/- 6% for the entire interval from 2.59 to 33.87 Ma, 1 σ).

To compliment this assessment of S_{obl} , we evaluate the magnitude of $\delta^{18}O$ obliquity variance relative to $\delta^{18}O$ precession variance (Supplementary Fig. 4d), and also relative to the combined $\delta^{18}O$ precession + $\delta^{18}O$ eccentricity variance (Supplementary Fig. 4e). Precession variance is quantified via power spectrum integration from 0.04 to 0.06 cycles/kyr (~25 to 17 kyr), and eccentricity variance is determined via integration from 0 to 0.012 cycles/kyr (the length of the window, 1 Myr, to ~83 kyr).

We recognise that the number of high-resolution astronomically-tuned data sets suitable for reliable S_{obl} assessment is small, given the required temporal resolution. Even in cases where sampling resolution is high, low sedimentation rates combined with bioturbation can obscure the true magnitude of obliquity forcing. The megasplice⁷ has been constructed from nine records with an objective of maximizing time-resolution and we consider it the best available estimate of S_{obl} . However, to examine the impact of regional influences and megasplice stitching points on the observed S_{obl} we provide complimentary analyses of new datasets from ODP Sites 982 (North Atlantic)⁴², 1146 (South China Sea)⁴³, 1264 (South Atlantic Walvis Ridge)⁹, and legacy data from 1218 (equatorial Pacific)⁸. The new dataset from Site

982 is an update of prior work (used in the megasplice), which includes splice revisions, new oxygen isotope data, and a new astronomical tuning³⁹; these results are consistent with the megasplice (Supplementary Fig. 5). The new dataset from Site 1146⁴⁰ allows a comparison with the latest Miocene Site 982 data (<8.56 Ma) used in the megasplice, and Site U1338 data (>12.825 Ma; equatorial Pacific)⁴⁴ that was used in the original megasplice. The results from Site 1146 confirm the presence of enhanced S_{obl} at 5.9 Ma, 9.2 Ma and 14 Ma (Supplementary Fig. 5d), in addition to increases in S_{obl} at 7.7 Ma and 15.9 Ma. Importantly, the largest S_{obl} occurs prior to 13 Ma, consistent with our interpretation of marine-based ice sheets with minimal sea ice fields.

The new data set⁹ from South Atlantic Site 1264/1265 is characterized by extremely low sedimentation rates (<1 cm/ky), and thus should be approached with caution. As expected, we observe an overall reduced magnitude of S_{obl} , consistent with low sedimentation rates and bioturbation that obscure the high-frequency obliquity forcing (Supplementary Fig. 5e). Nonetheless, the overall features observed in the Site 1264/1265 S_{obl} are generally consistent with the megasplice. The most substantial mismatch is within the interval from 22-24.5 Ma, where the megasplice shows a strong increase in S_{obl} , while Site 1264/1265 has a delayed maximum. Note, however, that the highest values of S_{obl} occur within the Miocene, consistent with our evaluation of the megasplice.

Finally, a complementary analysis of Site 1218 is included, using the original manually tuned astrochronology of ref.⁸. This permits analysis of a single record across the Oligocene-Miocene boundary. The results reveal good agreement with the megasplice, and an increase in S_{obl} at the Oligocene-Miocene boundary, although the obliquity response is likely muted by low sedimentation rates, and reduced data resolution (Supplementary Fig. 5f).

Based on these new analyses, we conclude that there is robust evidence for the major S_{obl}

features discussed in this work. As illustrated in Figures 1 and 4, the evaluation of S_{obl} provides a 1 million-year-average of different AIS ice extent scenarios, and thus integrates a wide range of spatial variability on shorter time scales; these averages potentially include outliers in some sectors of Antarctica, which we cannot discern at present. The assessment of S_{obl} in future studies, and integration with high-resolution studies of proximal geological records, will permit further constraint and evaluation of the model for AIS development proposed here.

All analyses utilize the *Astrochron* software for R^{45,46}; a script is available from the authors.

Ross Sea Stratigraphy. Correlations presented in Fig. 1 primarily utilise published data^{5,15,22}. However, recent biostratigraphic analysis of DSDP 270 has identified key biostratigraphic datums that identify a major disconformity (270-U2) at ~112 mbsf and constrain its duration from ~23 to 21 Ma (Supplementary Table 1). Ages for key diatom datums reported in DSDP 272⁴⁷ have been updated based on recent revisions to Southern Ocean diatom biostratigraphy and chronostratigraphy^{26,48}. All key events and horizons, their ages, and relevant references are presented in Supplementary Table 1.

Ocean Drilling Program Site 1165. A revised age model for Ocean Drilling Program Site 1165 is established herein (Supplementary Figure 3; Supplementary Table 2). Whereas the model uses previously published magneto-stratigraphy and diatom occurrences¹⁹, the maximum and minimum age range reported for the diatom datums are derived from the total, average, and hybrid range models of ref⁴⁸. We use the hybrid range model ages for tie points (marked by base of arrows in Supplementary Figure 3) to guide correlation of magnetic polarity reversals to the Global Polarity Time-Scale⁴⁹. Key tie points from this revised age model are used to correlate downhole resistivity data from hole 1165⁴ to the AND-2A drill core and the S_{obl} curve (Figure 3).

Diatom turnover. Diatom origination + extinction (turnover) rate (Fig. 1; Supplementary Fig. 2) is constructed from diatom occurrences recorded in drill cores from the Antarctic margin and Southern Ocean, and is expressed as the lineage-million-year rate that is insensitive to overall diversity⁵⁰. The turnover curve plotted is the ensemble median derived by bootstrap resampling of three models of diatom first- and last-occurrences in the Southern Ocean. The three models are based on 27 or 34 drill cores. This model ensemble approach captures uncertainties related to the position of the polar front over time, the nature of biases affecting the fossil record, the age calibration of drill cores, and the selection of species used in the analysis. Methodology and time series from 0 to 15 Ma are published²⁶ but the data series is extended here to 26 Ma and includes a major turnover event between 23.9 and 23.65 Ma (Fig. 1; Supplementary Fig. 2). Major turnover events coincide with proxy evidence for cooling and were driven by expansion of Antarctica's marine-based ice sheets and sea ice²⁶.

Data Availability

Datasets generated during and/or analysed during the current study are available in Supplementary tables 1 and 2 or from the corresponding author on reasonable request.

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486 **Figure 1: Integration of oxygen isotope data and Antarctic geological records from 35 to**

487 **5 Ma. a.** Deep sea oxygen isotope ($\delta^{18}\text{O}$) megasplice compilation⁷ provides a record of

488 Earth's climate system evolution (including temperature and ice volume) from 34 to 5 million

489 years ago. Evolutive Power Spectral Analysis of $\delta^{18}\text{O}$ megasplice, with power normalized

490 such that the maximum power in each 1 myr window is unity (deep red=maximum power,

491 deep blue=minimum power). Obliquity forcing variance and the $\delta^{18}\text{O}$ record are used to

492 calculate S_{obl} . Three phases of Antarctic ice sheet (AIS) evolution are reflected by S_{obl} and

493 include initial growth and subsequent variability of terrestrial continental ice sheets (black

494 horizontal arrow), episodic expansion of the AIS into marine environments (blue horizontal

arrow), and formation of more persistent perennial sea ice (red horizontal arrow). These phases coincide with intervals of high (800 – 600ppm), medium (600-400 ppm), and low (400-200 ppm) atmospheric CO₂. **b.** Selected time intervals showing correlation between *S_{obl}*, proximal Antarctic geological records including Southern Ocean diatom turnover and Ross Sea drill cores and δ¹⁸O data. Colours in drill core columns represent generalised stratigraphy (sinusoidal line = disconformity, dark green = grounding zone proximal diamictite, light green = distal glacial-marine diamictite, brown = sandstone with ice rafted debris, grey = mudstone). Vertical orange lines indicate inferred episodes of maximum marine ice sheet advance, which coincide with peaks in *S_{obl}*, regional disconformities, and δ¹⁸O maxima. Events in the late Oligocene and mid-Miocene also coincide with major diatom turnover events. Episodes that were dominated by ice sheets restricted to terrestrial land mass, ice on land and grounded below sea level, or ice on land and grounded below sea level with intervals of sea ice that extended well beyond the continental margin are indicated by black, blue, and red horizontal lines respectively (dashed lines indicate transitional intervals).

Figure 2: Antarctic location map with Ross Sea detail. Drill cores discussed in this paper include Cape Roberts Project (CRP) -2/2A and -3, ANDRILL (AND) -2A and -1B, Deep Sea Drilling Project (DSDP) Sites 270 and 272, and Ocean Drilling Program Site 1165. 1000 m bathymetric contour marks approximate position of modern continental shelf margin.

Figure 3: Correlation of Antarctic geological records and far-field data from the mid-Miocene. The AND-2A core from the Ross Sea continental shelf and downhole resistivity data from ODP Site 1165 offshore Prydz Bay are correlated with far field records including S_{obl} and sea level data from the New Jersey margin²⁵. Colours in drill core column represent generalised stratigraphy (see Fig. 1 caption for explanation). Vertical orange lines indicate inferred episodes of maximum marine ice sheet advance, which coincide with peaks in S_{obl} , regional disconformities, and $\delta^{18}O$ maxima. Indicators of ice margin retreat in AND-2A (mudstone) correlate with intervals of small variations in resistivity in 1165 and low S_{obl} , whereas indicators of ice advance (disconformities and diamictite) coincide with resistivity peaks and increasing/high S_{obl} . Indicators of AIS advance into marine settings also coincide with evidence for a distinct episode of sea level fall along the New Jersey Margin²⁵.

527

528 **Figure 4: Conceptual model outlining the influence of obliquity on ice sheet variability.**

529 Panels show AIS variability at glacial-interglacial frequencies as the ice sheet evolved over

530 the past 34 million years under high (A), medium (B), and low (C) atmospheric CO₂

531 conditions. Position of cross sections X-X'' indicated by orange line on maps. General

532 position of zonal wind systems indicated by circles with crosses (easterlies heading into page)

and dots (westerlies heading out of page); strength indicated by line thickness (heavier = stronger). ACC = Antarctic circumpolar current (flow direction out of page). ET = Ekman transport (dashed line = weaker flow). Red and green lines represent overturning circulation (larger arrows = enhanced upwelling). Dark blue 'lenses' represent cold dense bottom water and low salinity surface water. Generic isotherms shown by dashed white lines.

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Author Contributions R.L. and S.R.M. conceived the project. R.L., T.N., and R.M. performed the stratigraphic and proxy synthesis, and S.R.M. conducted time series analyses. N.G. conducted ice sheet model analysis. R.L. and S.R.M. wrote the first draft of the manuscript, in consultation with T.N., N.G., J.C., and R.M. All authors contributed to the interpretations and major findings of this work.

[SUPPLEMENTARY INFORMATION]

Supplementary Figure 1. Response of the Antarctic ice sheet to ocean forcing. a) Timeseries of ice thickness changes at the ANDRILL core site (red), compared to changes in thickness averaged over the Ross Sea (blue), and whole Antarctic continent (black) during the last episode of ocean-forced grounded ice sheet retreat. Thickness changes occurring at or near other deep geological drill sites are also shown for reference: Purple - Site 1165, Prydz Bay, and cyan - Site U1356, Wilkes Land margin. Note the close correspondence in timing of ice thickness changes in nearly all cases, at least at the millennial time-scale relevant to this study. b) Cross-plot of thickness changes comparing each of the four sites or areas shown in (a) to the Antarctic average. Whilst some degree of variability is evident, in all cases a highly-correlated quasi-linear relationship can be seen with none of the sites showing evidence of behaviour that is entirely independent of the ice sheet as a whole. Coefficients of Determination (CoD) show that in all cases, variability at each site can be used as a reliable indicator of whole-continent ice sheet variability.

Supplementary Figure 2. Turnover of diatoms in the Southern Ocean and Antarctic margin over the past 26 million years (Ma). Species lineage-million-year (lmy) turnover rate is the model ensemble and bootstrapped median (see Methods and ref. ²⁶ for details)

Supplementary Figure 3: Revised age model for Ocean Drill Program Site 1165 uses magneto-stratigraphic and biostratigraphic data from ref. ¹⁹ to correlate rock units to the

575 Global Polarity Time-scale (GPTS)⁴⁹. Stratigraphic units, downhole resistivity data⁴, and
576 magnetic reversal stratigraphy are shown at left. Key diatom (black arrow) and radiolarian
577 (open arrow) biostratigraphic data are summarized in Supplementary Table 2. The maximum
578 and minimum age range reported for these datums are derived from the total, average, and
579 hybrid range models of ref. ⁴⁸. Hybrid range model ages are marked by base of arrows.
580 Preferred correlation of magnetic reversals to the GPTS are indicated by crosses and connect
581 the line of correlation used in this study. Two disconformities between 700 and 750 m are
582 from ref. ¹⁹ and are marked by undulating lines.

583
584 **Supplementary Figure 4.** Obliquity Sensitivity (S_{obl}) analysis of the $\delta^{18}\text{O}$ Megasplice. (a)
585 Evolutive Power Spectral Analysis, with power normalized such that the maximum power in
586 each 1 myr window is unity (deep red=maximum power, deep blue=minimum power). (b) 40
587 kyr variance observed in the $\delta^{18}\text{O}$ megasplice. (c) Obliquity sensitivity (S_{obl}) measured using

the resampled theoretical obliquity solution (black line), and using the unresampled theoretical obliquity solution (red). The resampled theoretical solution (black line) restores some of the S_{obl} magnitude, as anticipated. More importantly, the major features are observed in both measures of S_{obl} . (d) The ratio of 40 kyr variance to precession scale variance in the $\delta^{18}\text{O}$ megasplice, (e) the ratio of 40 kyr variance to precession+eccentricity scale variance in the $\delta^{18}\text{O}$ megasplice. All analyses utilize three 2π prolate tapers, with a 1 myr moving window and a 10 kyr step. A linear trend is removed from each 1 myr window prior to analysis.

Supplementary Figure 5: Obliquity sensitivity analysis of the $\delta^{18}\text{O}$ Megasplice⁷, as compared to complementary data sets from specific sites. All analyses utilize three 2π prolate tapers, with a 1 myr moving window and a 10 kyr step. A linear trend is removed from each 1 myr window prior to analysis, and the theoretical obliquity solution is resampled

on the temporal grid of the individual data sets (see Methods). **(a)** $\delta^{18}\text{O}$ Megasplice, **(b)** obliquity sensitivity determined for the $\delta^{18}\text{O}$ Megasplice, **(c)** obliquity sensitivity determined for an updated $\delta^{18}\text{O}$ data set from Site 982 in the North Atlantic⁴², using their “FT” time model, **(d)** obliquity sensitivity determined for an updated $\delta^{18}\text{O}$ data set from Site 1146 in the South China Sea⁴³, using their eccentricity-tilt tuning, **(e)** obliquity sensitivity determined for a new $\delta^{18}\text{O}$ data set from Sites 1264/1265 on the South Atlantic Walvis Ridge⁵¹, using their eccentricity-based tuning, **(f)** obliquity sensitivity determined for the $\delta^{18}\text{O}$ record from Site 1218 in the tropical Pacific⁸, using their manual tuning to an eccentricity-tilt-precession model. Results for the individual records are plotted using the same axis scaling, to allow direct comparison of observed $\delta^{18}\text{O}$ obliquity sensitivity.

Supplementary Table 1. Key Ross Sea stratigraphic events

Surface/event	description	depth	Correlation	age/duration	Ref.
lithostratigraphic boundary	First diamictite /evidence of subglacial erosion	300 mbsf (CRP-3)	Oi1a	32.8 Ma	⁵
V4/V5; Rc (yellow)	major seismic reflector	443 mbsf (CRP-2A)		30 Ma	⁵²
Sequence 11	glacial/interglacial cycle	310-242 (CRP-2)	C7n.2n	24.474 to 24.109 Ma	²²
Sequence 10	glacial/interglacial cycle	185-242 (CRP-2A)	C7n.1n	24 to 23.962 Ma	²²
Rd (brown)	major seismic reflector + disconformity	186 mbsf (CRP-2A)		24.0 to 23.3Ma	^{22,53}
Sequence 9	glacial/interglacial cycle	130-185 mbsf (CRP-2)	just above C6Cn.2r/C6Cn.3n	23.295-23.030 Ma	²²
Re (purple)	major seismic reflector + disconformity	130 mbsf (CRP-2)	Oligocene/Miocene boundary	< 23.03 Ma	^{22,53,54}
LO <i>D. bissectus</i>	calcareous nannofossil last occurrence	150.65 mbsf (DSDP 270)		23.13 Ma	Herein
Change in foram assemblage	HTC - EEN	121 mbsf (DSDP 270)	Oligocene/Miocene boundary		⁵⁵

DSDP 270 U2	unconformity/time missing	~112 mbsf	Mi1	~23 to 21 Ma	Herein
FO <i>B. cooperii</i>	dinocyst first occurrence	111 mbsf (DSDP 270)		20.7 Ma	⁵⁶ Herein
U2-A2A	disconformity	774.94 mbsf (AND-2A)	Mi1b	18.7 to 17.8 Ma	¹⁵
lithostratigraphic boundary	Transition from proximal grounding zone facies (motif 2) to ice distal facies (motifs 3 and 4)	637.96 mbsf (AND-2A)	C5Dn	17.533 to 17.235 Ma	^{15,57}
U3-A2A	disconformity	262.57 mbsf (AND-2A)		15.8 to 14.6 Ma	¹⁵
FO <i>D. lauta</i>	diatom first occurrence	157.02 mbsf (DSDP 272)	FAD <i>D. lauta</i>	15.72 Ma	^{26,47}
FO <i>A. ingens</i>	diatom first occurrence	158.72 mbsf (DSDP 272)	FAD <i>A. ingens</i>	15.83 Ma	^{26,47}
FO <i>D. maccollumi</i>	diatom first occurrence	146.5 to 148 mbsf (DSDP 272)	FAD <i>D. maccollumi</i>	17.05 Ma	^{26,47}
FO <i>D. simonsenii</i>	diatom first occurrence	146.5 to 148 mbsf (DSDP 272)	FAD <i>D. simonsenii</i>	14.48 Ma	^{26,47}
RSU 4	major seismic reflector + disconformity	~145 mbsf (DSDP 272)		16 to 14.1 Ma; <15.7 to 14.5 Ma	¹² Herein
range of <i>N. denticuloides</i>	diatom range	84.5 to 62.5 mbsf (DSDP 272)		>11.73 < 14.42 Ma	^{26,47}
U4-A2A		214 mbsf (AND-2A)		14.4 to 9.7 Ma	¹⁵
RSU's 1-3	amalgamated seismic reflectors + disconformity	30 mbsf (DSDP 272)		<13.8 Ma	¹²

613

614 **Supplementary Table 2:** Biostratigraphic data used to establish the age model for ODP 1165
615 presented in this paper (see Supplementary Figure 3). Diatom and radiolarian occurrence data
616 from ref. ⁵² and age data from ref. ⁴⁸

Depth (m)	Event	Description	Type	Age (Ma)
274.05	A	<i>Denticulopsis hyalina</i>	FAD	14.14 to 14.73
280.80	B	<i>Nitzschia denticuloides</i>	FAD	13.53 to 13.71
289.64	C	<i>Cycladophora humerus</i>	FAD	13.65 to 13.72
297.45	D	<i>Denticulopsis simonsenii</i>	FAD	14.14 to 14.17
318.03	E	<i>Actinocyclus ingens</i> var. <i>nodus</i>	FAD	14.42 to 14.57

390.05	F	<i>Nitzchia grossepunctata</i>	FAD	15.08 to 16.23
449.25	G	<i>Actinocyclus ingens</i>	FAD	15.05 to 15.96
478.79	H	<i>Cycladophora golli regipileus</i>	FAD	18.0 to 18.05
487.00	I	<i>Denticulopsis maccollumii</i>	FAD	16.23 to 17.03
512.7	J	<i>Crucidentricula ikeibei</i>	FAD	17.93 to 18.01
569.75	K	<i>Thalassiosira praeфрага</i>	LAD	17.94 to 17.95
753.77	L	<i>Thalassiosira praeфрага</i>	FAD	18.46 to 18.58