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Authors:

Stephen Barker, School of Earth and Environmental Sciences, Cardiff University, UK barkers3@cf.ac.uk

Aidan Starr, School of Earth and Environmental Sciences, Cardiff University, UK
aidan.m.starr@gmail.com

Jeroen van der Lubbe, Department of Earth Sciences, Vrije Universiteit Amsterdam, Netherlands
h.j.l.vander.lubbe@vu.nl

Alice Doughty, School of Earth and Climate Sciences, University of Maine, USA
alice.doughty@maine.edu

Gregor Knorr, Alfred Wegener Institute, Bremerhaven, Germany grgorknorr@hotmail.com

Stephen Conn, School of Earth and Environmental Sciences, Cardiff University, UK sgconn@gmail.com

Sian Lordsmith, School of Earth and Environmental Sciences, Cardiff University, UK
golaucymru@gmail.com

Lindsey Owen, School of Earth and Environmental Sciences, Cardiff University, UK
OwenL5@cardiff.ac.uk

Alexandra Nederbragt, School of Earth and Environmental Sciences, Cardiff University, UK
NederbragtA@cardiff.ac.uk

Sidney Hemming, Lamont-Doherty Earth Observatory, Columbia University, USA
sidney@ldeo.columbia.edu

Ian Hall, School of Earth and Environmental Sciences, Cardiff University, UK Hall@cardiff.ac.uk

Leah Levay, International Ocean Discovery Program, Texas A&M University, USA levay@iodp.tamu.edu

IODP Exp 361 Shipboard Scientific Party (See Supplementary Materials)

This manuscript has been accepted for publication in *Science*. This version has not undergone final editing. Please refer to the complete version of record at <http://www.sciencemag.org/>. The manuscript

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Persistent influence of precession on northern ice sheet variability since the early Pleistocene

One-sentence summary: Precession-driven mass wasting of northern ice sheets became synonymous with glacial termination during the MPT

Authors:

Stephen Barker^{1*}, Aidan Starr¹, Jeroen van der Lubbe², Alice Doughty³, Gregor Knorr⁴, Stephen Conn¹, Sian Lordsmith¹, Lindsey Owen¹, Alexandra Nederbragt¹, Sidney Hemming⁵, Ian Hall¹, Leah Levay⁶ and the IODP Exp 361 Shipboard Scientific Party^{**}

¹ School of Earth and Environmental Sciences, Cardiff University, UK

² Department of Earth Sciences, Vrije Universiteit Amsterdam, Netherlands

³ School of Earth and Climate Sciences, University of Maine, USA

⁴ Alfred Wegener Institute, Bremerhaven, Germany

⁵ Lamont-Doherty Earth Observatory, Columbia University, USA

⁶ International Ocean Discovery Program, Texas A&M University, USA

*Corresponding author: barkers3@cf.ac.uk

**See Supplementary Materials

Abstract (125 words)

Before ~1M years ago, variations in global ice volume were dominated by changes in obliquity but the role of precession remains unresolved. Using a record of North Atlantic ice rafting spanning the last 1.7Myr, we find that the onset of ice rafting within a given glacial cycle (reflecting ice sheet expansion) consistently occurred during times of decreasing obliquity, while mass ice wasting (ablation) events were consistently tied to minima in precession. Furthermore our results suggest that the ubiquitous association between precession-driven mass wasting events and glacial termination is a unique feature of the mid/late Pleistocene. Before then, (increasing) obliquity alone was sufficient to end a glacial cycle,

before losing its dominant grip on deglaciation with the southward extension of northern hemisphere ice sheets since ~1Ma.

Main text (3,499 words)

Glacial cycles of the mid to late Pleistocene (approximately the last 0.7Myr) were characterized by their long (~100kyr) duration and relatively abrupt (~10kyr) termination (1). Their ~100kyr periodicity has stimulated debate as to which orbital parameters (if any) are most important in driving glacial-interglacial (G-IG) variability, given that direct orbital forcing at this frequency (eccentricity) is negligible (2) (Fig. 1). However, there is growing consensus that both precession and obliquity play a role (at least in glacial termination) through their combined influence on summer insolation across northern high latitudes (3-5). Prior to the Mid Pleistocene Transition (MPT; 1.25-0.7Ma) the situation was, at face value, more straightforward; G-IG variability was dominated by ~41kyr cyclicity, reflecting the near-linear control of ice sheet growth and decay by changes in axial tilt (giving rise to stronger or weaker seasonality) (6). On the other hand, the lack of a clear precession signal in pre-MPT G-IG cyclicity makes little sense because precession plays a substantial role (dependent on the metric employed; Fig. 1) in modulating northern-hemisphere summer insolation, which is often considered to be the most important factor in the growth and decay of large continental ice sheets (3, 7, 8).

Building on this premise, Raymo, Lisiecki and Nisancioglu (9) proposed that the 'missing' precession signal expected in pre-MPT records of benthic foraminiferal $\delta^{18}\text{O}$ (a 1st order proxy for global ice volume) might be obscured by the equal and opposite effects of northern versus southern hemisphere ice sheet variability on mean ocean $\delta^{18}\text{O}$ i.e. the interhemispheric asymmetry of precession effectively cancelled out variations on this timescale in the record of global ice volume while equivalent variations in the obliquity band (which are in-phase between north and south) were amplified. The elegant proposition of

(9) is ultimately testable; records of northern (and southern) ice sheet variability should display strong fluctuations on precession timescales.

Searching for precession in early Pleistocene ice sheet variability

To this end we have produced a record of ice rafted debris (IRD) accumulation from NE Atlantic ODP Site 983 (60.4°N, 23.6°W, 1983m; Fig. S1), extending the previous record (10-12) by 500kyr back to 1.7Ma (13). The complete record comprises 9,389 samples with an average temporal resolution of 181 years. We employ three independent approaches for age model construction (13). Firstly, we utilize the age model constructed by Lisiecki and Raymo (14) for ODP Site 983 as part of their benthic $\delta^{18}\text{O}$ stack (LR04). The LR04 age model was constructed by tuning to a target derived using a simple ice sheet model driven by June 21 insolation at 65°N (a signal dominated by precession; Fig. 1). This implies that any orbital frequencies present in records using the LR04 timescale should be detectable but also risks introducing frequencies that might not exist in nature. We therefore derive a second age model (U1476pMag; Fig. S2) based on the growing body of absolutely-dated magnetic polarity reversals and magnetic excursions (15) and a new record of benthic $\delta^{18}\text{O}$ from IODP Site U1476 in the western Indian Ocean (15.8°S, 41.8°E, 2166m) (13). The frequency of age constraints available for this approach is relatively low (Table S1), resulting in relatively large (mean 16kyr 1σ) age uncertainties (Fig. S3) (13). However, the calculated absolute offset between U1476pMag and LR04 over the last 1.8Myr averages only 6.6kyr (maximum 16kyr), suggesting good agreement between these two completely independent approaches. Finally, we derive a third timescale for our record based on the precession-tuned age model developed for 'Shackleton' site IODP U1385 (37.6°N, 10.1°W, 2578m) (13, 16). Although this model is also orbitally tuned, it is independent of LR04 and as such, provides a useful comparison (Figs. S4, S5).

The record of IRD accumulation from ODP Site 983 is shown in Figure 2. IRD accumulation is plotted on a log scale to highlight variations during periods of relatively low accumulation when ice sheets are small (i.e. interglacial periods). It has been suggested (9) that the apparent absence of precession (and domination of obliquity) frequencies in pre-MPT records of ice rafting from the North Atlantic could be due to the fact that most ice rafting occurs during deglaciation, when rising sea level can destabilize marine-based ice sheets (i.e. iceberg calving rates on North Atlantic marine-based ice margins are controlled primarily by sea level and hence are expected to follow the sea level record even if land-based ice sheets themselves vary on different timescales). Indeed, we typically observe the highest levels of IRD accumulation during terminal events, when sea level is rising (Fig. S6; (13)). This leads to an apparent lag of IRD accumulation (non-log-transformed) behind sea level (in this case the LR04 stack) on G-IG timescales. On the other hand, we observe no such lag when comparing log IRD with the LR04 stack (13). In fact, we observe coherency between log IRD and the LR04 stack on G-IG (at ~ 41 kyr and subsequently ~ 100 kyr) timescales throughout the last 1.7Myr (Figs. 2, S17). We suggest this reflects the fact that, following peak interglacial conditions, ice rafting increases as ice sheets expand to form more extensive marine-based margins and we note (using an algorithm to identify the start and end of significant ice rafting during each glacial cycle (13)) that the onset of significant ice rafting tends to occur within a narrow range of benthic $\delta^{18}\text{O}$ ($3.9 \pm 0.2\%$, Fig. 2), and continues throughout much of the subsequent glacial period. We therefore conclude that our record of ice rafting (log IRD) reflects variations in the size and/or lateral extent of circum-NE Atlantic ice sheets rather than sea level per se. Specifically, although ice rafting always represents ice sheet ablation (via iceberg calving), we suggest that the increase in ice rafting following an interglacial reflects net growth/extension of ice sheets, while the end of ice rafting reflects ice sheet recession before the next interglacial.

We test for the presence of significant (>90% confidence level, CL) frequencies in our records of IRD and benthic $\delta^{18}\text{O}$ (plus the LR04 stack) for different intervals and age models using 3 methods (13) (Figs. 3, S12-S14): a multi-taper method (MTM) autoregressive -AR(1)- model (17, 18), an alternative spectral noise estimation method (LOWSPEC (18)) and an MTM harmonic F-test, which is independent (to first order) of the first two (18). We also perform continuous wavelet transforms on each dataset to allow visualization of its temporal evolution (Fig. S16). In summary, while we find strong power in the obliquity band of NE Atlantic ice rafting before the MPT (1.7 to 1.25Ma), we observe no significant (>90% CL) peaks in the precession band prior to 1.25Ma. We note that some power in the precession band is observed using the U1385 age model (which extends back to 1.43Ma; Fig. 3) but no peaks in this range pass the various significance tests we apply (13) (Fig. S15). Recent work (19) suggests that traditional spectral analysis techniques may be too insensitive for isolating precession frequencies in pre-MPT records but we note that the methods we employ do identify significant (>90% CL) precession-like peaks (albeit with relatively low power) within the LR04 stack and the benthic $\delta^{18}\text{O}$ record from U1476 even on its absolute (non-orbitally tuned) U1476pMag age model (Fig. 3), which suggests (in agreement with ref (19)) that precession probably played some role in early Pleistocene benthic $\delta^{18}\text{O}$ variability, either through an influence on ice volume or deep ocean temperature. On the other hand, our results from spectral analysis suggest that circum-NE Atlantic ice sheets did not fluctuate strongly at precession frequencies before the MPT. Moreover, the accumulation of IRD at our site rarely falls to zero for more than a few thousand years (Figs. S8, S9), suggesting that marine-proximal ice sheet margins existed even during interglacial periods throughout the last 1.7Myr. Thus, it is unlikely we are missing a precession signal derived from purely terrestrial ice sheets. In summary, while we cannot rule out the prediction (9) that pre-MPT ice sheets varied strongly at precession frequencies, we find little evidence to support it. However, closer visual inspection of the IRD record reveals an alternative picture, as we discuss below.

Ice sheet ablation driven by precession

In Figure 4 the record of IRD is plotted on its three independent age models, together with the beginning and end of significant ice rafting for each glacial cycle as determined by our algorithm (Figs. S7-10) (13). Note that the end of ice rafting within a given cycle is defined as the end of the latest phase of significant ice rafting lasting 2,800 years (13) or more prior to the subsequent interglacial (defined as a minimum in LR04 $\delta^{18}\text{O}$ with absolute value $<4.25\text{‰}$ (13)). This is because we wish to identify the major ice rafting events (i.e. mass ablation events) that are characteristic of mid/late Pleistocene glacial terminations (11, 20, 21). For our purposes, we name these ‘terminal ice rafting’ (TIR) events, meaning that they represent the last major episode of ice rafting within a glacial cycle, even if (as we describe below) they do not always coincide with the transition to interglacial conditions.

In Figure 5 we assess the start and end of ice rafting with respect to the phase of precession and obliquity. We find a consistent link between TIR events and precession over the last 1.7Myr (Table S2), with the end of TIR events occurring on average $0.2 \pm 2.4\text{kyr}$ (95% CI, when combining events from the three age model approaches (13)) before minima in precession prior to 1Ma and $0.9 \pm 2.0\text{kyr}$ behind precession minima since 1Ma. Combining all instances we find that TIR events ended on average $0.5 \pm 1.5\text{kyr}$ behind minima in precession over the last 1.7Myr. Since TIR events are (by our definition) 2.8kyr or more in duration, our findings imply that large-scale ablation of northern ice sheets typically coincided with increasing to maximum summer insolation as a function of precession throughout the last 1.7Myr. Notably this conclusion could not be drawn using traditional spectral analytical techniques, which are designed to detect periodic waveforms rather than the timing of discrete events.

A different relationship is observed with obliquity (Table S2). Before 1Ma, TIR events tended to end while obliquity was increasing (ending on average 8.3 ± 2.4 kyr before a peak in obliquity; Fig. 5) but since 1Ma, their ending has been more closely aligned with maxima in obliquity (offset = 0.3 ± 3.4 kyr; Fig. 5). On the other hand, deglacial transitions in benthic $\delta^{18}\text{O}$ have been closely aligned with maxima in obliquity throughout the last 1.7Myr (average offset between mid-point of deglaciation and maximum obliquity = 2.3 ± 1.7 kyr; Fig. S11) (13). The association of post-MPT TIR events with insolation maxima as a function of both obliquity and precession (as described above) provides additional support for a dual role of obliquity and precession in driving mid/late Pleistocene glacial terminations (4). However, the situation seems to have been different before that time.

Terminal ice rafting events and deglaciation

Our results suggest that precession has played a persistent role in TIR events since the early Pleistocene. However, before 1Ma those events were not always aligned with deglacial transitions according to benthic $\delta^{18}\text{O}$ (Fig.6); Over the last 1Myr the end of TIR events corresponded closely with the latter half of deglaciation as defined by the corresponding decrease in benthic $\delta^{18}\text{O}$ (Fig. 6C) i.e. mass ice sheet wasting coincided with the transition to interglacial conditions. Prior to 1Ma, however, TIR events tended to end earlier with respect not only to obliquity (Fig. 5) but also to deglaciation as constrained by benthic $\delta^{18}\text{O}$ (Fig. 6C, Table S2; note this result is insensitive to the age model employed). Barker *et al.* (12) identified a termination-like event (T14.1 in Fig. 4) ~ 1.05 Ma within Marine Isotope Stage (MIS) 30. While it was conceded that T14.1 could not be a true termination in the sense that it did not coincide with decreasing benthic $\delta^{18}\text{O}$, the event notably bore other hallmarks of late Pleistocene terminations, including widespread ice rafting followed by an abrupt warming across the NE Atlantic. It was also noted

that TIR event T14.1 was aligned with a maximum in northern-hemisphere summer insolation that was a function of precession (i.e. a minimum in the precession parameter) and not obliquity.

Our record suggests that this pattern was relatively common before 1Ma. In fact, prior to that time TIR events commonly ended before the decrease in benthic $\delta^{18}\text{O}$ typically taken to represent deglaciation (Fig. 6C). Our results therefore suggest that prior to 1Ma, TIR events were not synonymous with deglaciation (the transition to interglacial conditions). Furthermore, whether or not a TIR event coincided (or even overlapped) with deglaciation before 1Ma depended on the phasing between obliquity and precession, as we discuss below.

In Figure 6D we plot the temporal offset between the mid-point of each deglaciation and the end of its associated TIR event versus the offset between the obliquity peak closest to that deglaciation and its nearest minimum in precession. Throughout the last 1.7Myr the end of a TIR event tended to coincide (within a few kyr) with the mid-point of deglaciation when the closest precession minimum occurred prior to the peak in obliquity (a negative obliquity-precession offset in Fig. 6, e.g. events ii and iii). On the other hand, since 1Ma, when the closest precession minimum occurred after the peak in obliquity (a positive obliquity-precession offset in Fig. 6, e.g. event i) the TIR event (more often than not) continued beyond the mid-point of deglaciation (Fig. 6D), presumably driven by the precession minimum directly following the maximum in obliquity (Fig. 6E). Moreover, before 1Ma, the same positive obliquity-precession offset typically produced a TIR event that ended up to 10-20kyr before the mid-point of deglaciation (Fig. 6D, e.g. events iv and v), apparently driven by the preceding minimum in precession (Fig. 6E). Thus, since 1Ma, TIR events have always coincided with deglacial transitions but prior to 1Ma, a TIR event might start and end before deglaciation had even begun, if the obliquity-precession offset was positive.

The decoupling observed between TIR events and deglaciation prior to 1Ma suggests that while obliquity may have been responsible for the majority of deglacial ice sheet ablation prior to the MPT, the most conspicuous ice rafting events (at least across the NE Atlantic) were a result of precession forcing. We suggest this reflects the difference between precession and obliquity in their influence on the spatiotemporal distribution of insolation (Fig. 1); while obliquity has a greater effect on integrated summer energy over higher latitudes (which could explain its dominant control on the net waxing and waning of high latitude ice sheets prior to the MPT), precession drives larger changes in the intensity of peak summer warmth at lower latitudes, which could explain why it is so effective at driving massive iceberg calving events along the southern margins of large ice sheets (even if these had little impact on the overall volume of land-based ice prior to 1Ma).

Our results therefore imply a change in the influence of obliquity over deglaciation across the MPT. Specifically, before 1Ma, ice sheets were apparently unable to survive a maximum in obliquity such that a subsequent minimum in precession would have little left to melt (in terms of marine-terminating ice sheets) thus the preceding precession-driven ablation event (that occurred when ice sheets were still large; Fig. 6E) was the last within that cycle. After 1Ma, sufficient ice apparently remained even after the peak in obliquity associated with deglaciation, such that a subsequent minimum in precession could drive further ablation and ice rafting. In summary, it seems that precession minima will always drive ice ablation events if sufficient ice exists and whether or not this is the case depends on the influence of obliquity over deglaciation, which weakened across the MPT. Such a change implies the growth of larger northern hemisphere ice sheets since ~1Ma (which required more energy to melt e.g. (5)) and/or their net migration towards lower latitudes, where the effects of obliquity are weaker and those of precession stronger (Fig. 1). In turn this could reflect the proposed net increase in flux of Atlantic surface

waters entering the Nordic Seas (the Atlantic Inflow) since ~ 1.2 Ma, promoting enhanced moisture transport and the growth of larger ice sheets with an increasingly southern influence (12).

A notable exception to the 'pre-1Ma' pattern described above occurred ~ 1.2 Ma (Fig. 4). Although TIR event T17 coincided with the deglacial transition into MIS 35, neither event was associated with a maximum in obliquity (according to two out of the three age models we employ), occurring instead on the next downward limb of obliquity and coincident with a minimum in precession ~ 1.19 Ma. Moreover (and according to all three age models) the subsequent minimum in obliquity (~ 1.18 Ma) was the only minimum in the past 1.7Myr not to have been associated with the onset or continuation of significant ice rafting (Fig. 2), which we suggest could reflect the late occurrence of T17. Ultimately the result was the appearance of glacial cycles substantially exceeding ~ 41 kyr in duration (Figs. 3, 4), marking the weakening grip of obliquity on G-IG variability and the beginning of the MPT.

We suggest that our observation of a direct link between the temporal offset of TIR events versus deglaciation and the phasing of obliquity versus precession (Fig. 6) provides the strongest evidence yet for the influence of precession -in addition to obliquity- on ice sheet variability during the early Pleistocene. This is highlighted by a test for significance of the relationship >1 Ma (Fig. 6D). Using the surrogateCor function in Astrochron (22) we obtain a correlation coefficient of -0.73 ($p < 0.005$) (13), meaning we can state with confidence that the timing of TIR events versus deglaciation prior to 1Ma was related to the phase of precession with respect to obliquity.

Pre-MPT precession signal obscured by obliquity

Based on a detailed study of the last 0.8Myr, Tzedakis and colleagues (23) concluded that glacial inception (the start of a glacial period) is strongly tied to periods of decreasing obliquity, emphasizing the importance of milder northern-hemisphere summers (and winters) for the growth and survival of terrestrial ice masses at high latitudes. Our results extend that conclusion to the past 1.7Myr; the onset of significant ice rafting (implying that ice sheets have grown large enough to develop extensive marine-based margins) is aligned with decreasing to low obliquity in almost all cases (Fig. 5). Conversely our results do not allow us to determine an unambiguous link between precession and the onset of ice rafting (Fig. 5).

Because decreasing obliquity appears to be critical for glacial inception, this places an upper limit of 1/41kyr on the frequency of glacial cycles throughout the last 1.7Myr (a possible exception is the interval of high frequency -precession-like- variability ~1Ma when three 'inception' events occurred across two obliquity cycles; Fig. 2). Hence although our results suggest that precession has played a persistent role in the ablation of marine terminating ice sheets since 1.7Ma, we should not be surprised by the lack of a strong precession signal in the frequency domain of pre-MPT G-IG variability.

Emergence of glacial terminations across the MPT

The global impacts related to TIR events during the mid to late Pleistocene are well documented, for example abrupt shifts in ocean circulation (11, 20), changing greenhouse gas concentrations (11, 24) and global precipitation patterns (24, 25) are all thought to occur in tandem with major North Atlantic ice rafting during glacial termination. Our results suggest that these impacts may also have been prevalent in the ~41kyr world. For example, we observe features within the records of benthic foraminiferal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ from IODP Site U1476 that match the timing of major IRD events at Site 983 including some

that did not lead directly to deglaciation (Fig. 4). The record of $\delta^{18}\text{O}$ from Site U1476 itself displays an excellent correlation with the LR04 stack (13) suggesting that it represents a reasonable reflection of global mean ocean composition. Thus, the commonality between such distal and diverse proxy records (between IRD accumulation in the North Atlantic and proxies for deep ocean chemistry and circulation in the Indian Ocean; Fig. S1) attests to the wider significance of our record from Site 983 i.e. the events we record are probably not just a local phenomenon.

Our results therefore suggest that precession-driven mass ice ablation events have occurred since the early Pleistocene, with related effects on a global scale. On the other hand, their ubiquitous association with deglaciation is a phenomenon unique to the mid/late Pleistocene. Specifically, we suggest that prior to the MPT, obliquity alone was sufficient to end a glacial cycle (as evidenced by the fact that subsequent peaks in precession did not drive further ablation). However, since then all deglaciations have been associated with precession-driven mass ablation events, which we attribute to the increased importance of precession for melting the larger proportion of northern hemisphere ice sheets situated at lower latitudes since the MPT. We therefore recommend that the term glacial termination (*sensu stricto*) be reserved for deglaciations of the mid to late Pleistocene, which involve the mutual interplay between maxima and minima in obliquity and precession, respectively.

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Acknowledgements

We thank M. Crucifix for assistance in implementing Palinsol. **Funding:** We acknowledge financial support from UK-NERC (awards NE/P000878/1, NE/L006405/1, NE/J008133/1 to SB), the Philip Leverhulme Trust and the Comer Science and Education Foundation (award GCCF3). **Author contributions:** SB designed and managed data collection, analyzed datasets and drafted manuscript and figures. SC and SL performed all laboratory work on ODP 983. SC, SL and LO performed all laboratory work on U1476. AN measured benthic isotopes in U1476. SB, AS and JvdL developed age models. GK, AD, AS, JvdL, SH, IH and LL edited text. All members of the IODP Exp 361 shipboard Scientific Party assisted in the collection of the U1476 cores. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** All data are available in the Supplementary Material. This research used samples provided by the Integrated Ocean Drilling Program (IODP). We thank the curators at Bremen and Texas A&M core repositories for assistance in sampling and curation. This is Cardiff EARTH CRediT contribution #1.

List of Supplementary Materials

IODP Exp 361 Shipboard Scientific Party information

Materials and Methods

Tables S1, S2

Figs. S1 – S17

Supplementary Dataset S1

Matlab files.zip

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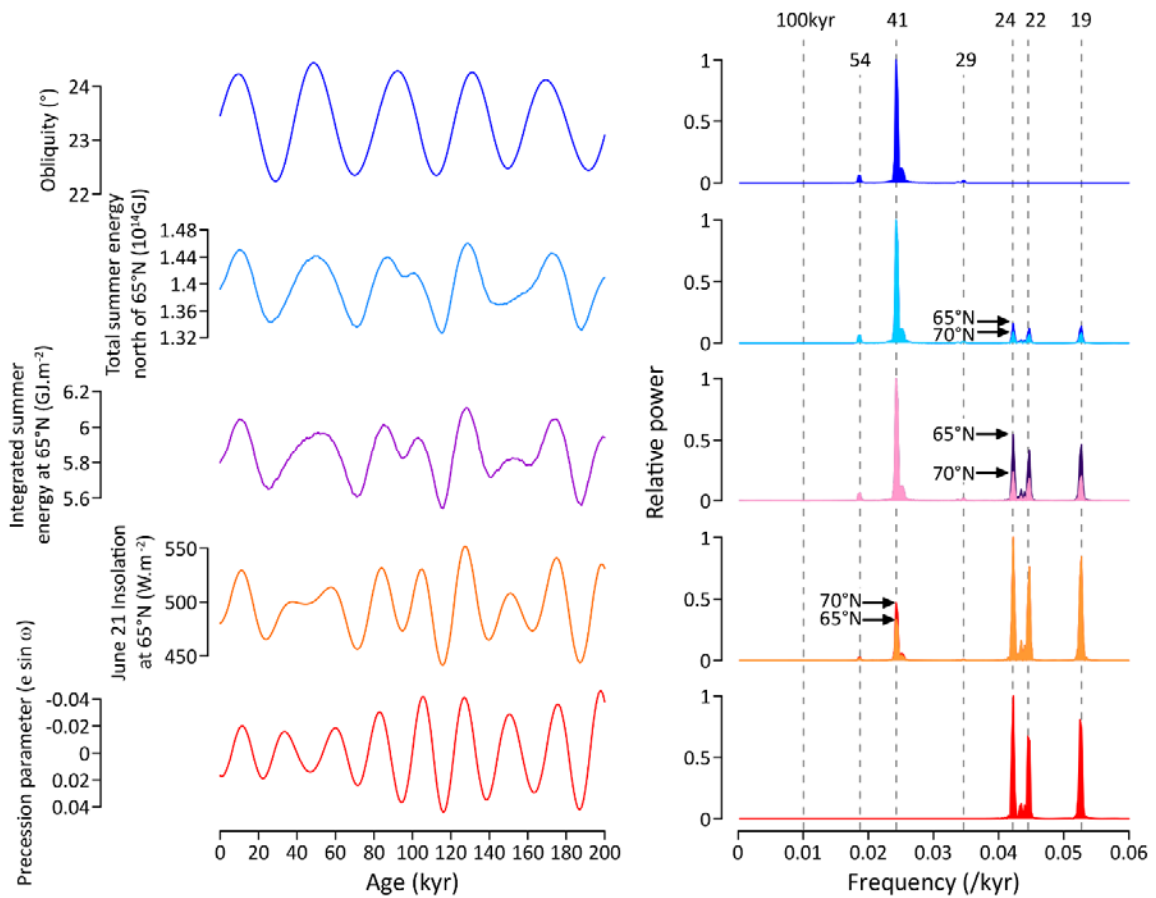


Figure 1. Influence of obliquity and precession on the spatiotemporal distribution of incoming solar radiation. Left: variations in axial tilt (obliquity) and precession (26) with various metrics for assessing changes in northern summer insolation (13). Note that a negative value of the precession parameter is associated with a positive anomaly in northern hemisphere summer insolation. Right: power spectra for obliquity, precession and insolation metrics at 2 different latitudes. All metrics display significant (>99% CL according to the various tests outlined by (18)) power in the obliquity and precession bands with increasing power in the precession band relative to obliquity at lower latitudes. Power spectra are

normalized to the maximum power in each case. Vertical dotted lines in right panel are expected orbital periods in kyr (note no metric displays substantial power at ~100kyr).

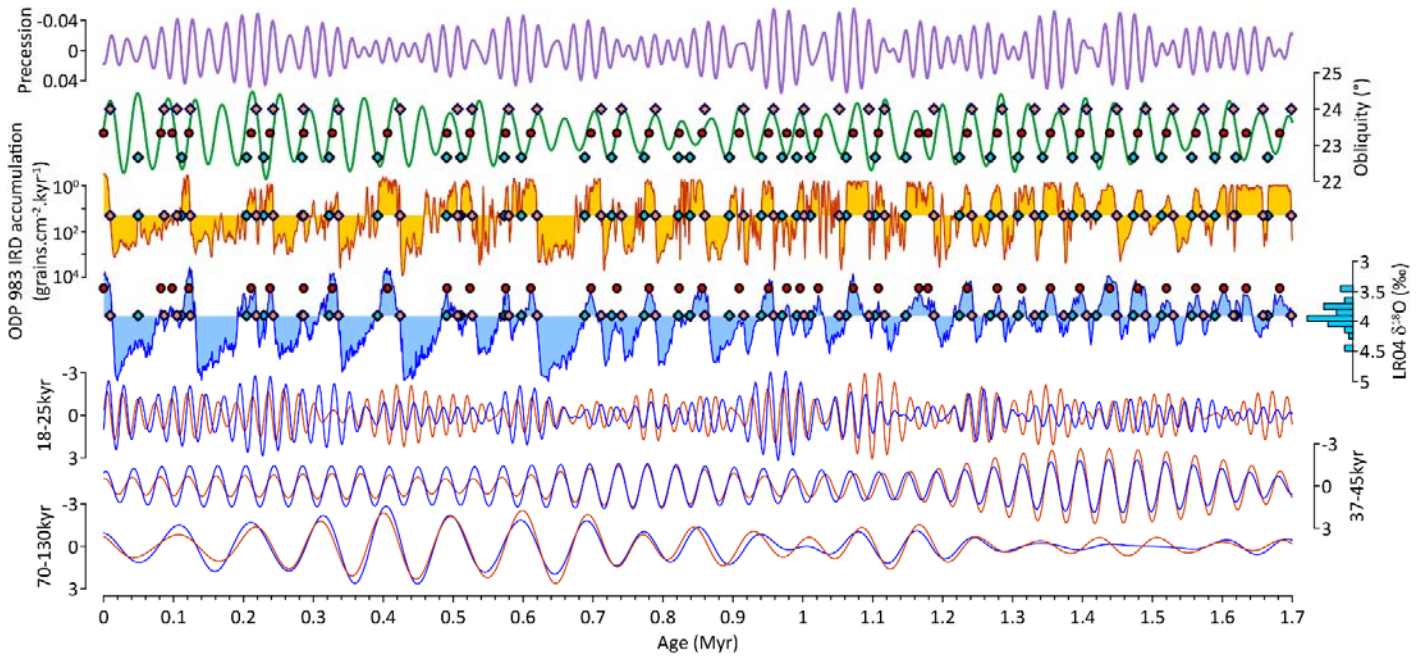


Figure 2. 1.7Myr of ice rafting across the NE Atlantic. Throughout: red circles are interglacials (as determined by our algorithm (13)), blue diamonds represent onset of significant ice rafting (see orange-filled curve), orange diamonds represent end of TIR events (13). From top to bottom: precession (26), obliquity (26), IRD accumulation from ODP 983 on the LR04 age model (data have been smoothed and detrended to highlight intervals of significant ice rafting (13)), LR04 benthic stack (histogram represents values of $\delta^{18}\text{O}$ at time of each IRD onset, mean= $3.9 \pm 0.2\text{‰}$ as indicated by horizontal fill threshold of LR04 curve), 18-25kyr, 37-45kyr and 70-130kyr filter outputs of log IRD (red) and LR04 stack (blue). Note coherence between LR04 stack and log IRD on G-IG (41kyr and subsequently $\sim 100\text{kyr}$) timescales throughout the last 1.7Myr (see also Fig. S17).

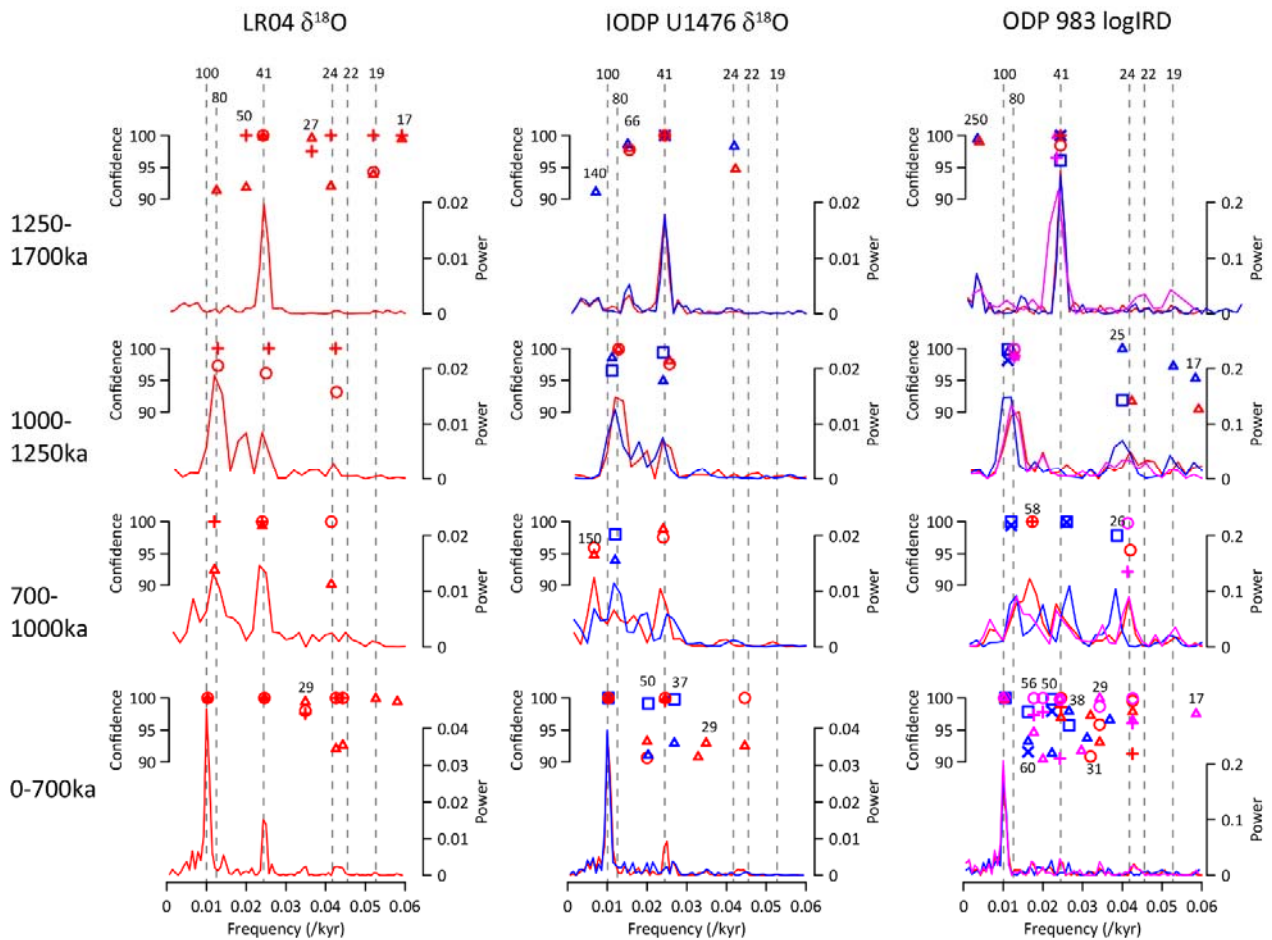


Figure 3. No significant precession periodicity in pre-MPT ice rafting. Illustrative power spectra and significant spectral peaks identified in LR04, U1476 benthic $\delta^{18}\text{O}$ and ODP 983 log IRD for 4 distinct time windows using 3 timescales and 3 different spectral methods. Red, blue and magenta represent LR04, U1476pMag and U1385 timescales respectively. Circles and squares represent results using LOWSPEC (13, 18), crosses and exes use the robust AR1 method (17, 18) and triangles represent the MTM harmonic F-test (13). No statistically significant (>90% CL) precession-like peaks are identified in the pre-MPT (1250-1700ka) section of log IRD while they are present in records of benthic $\delta^{18}\text{O}$.

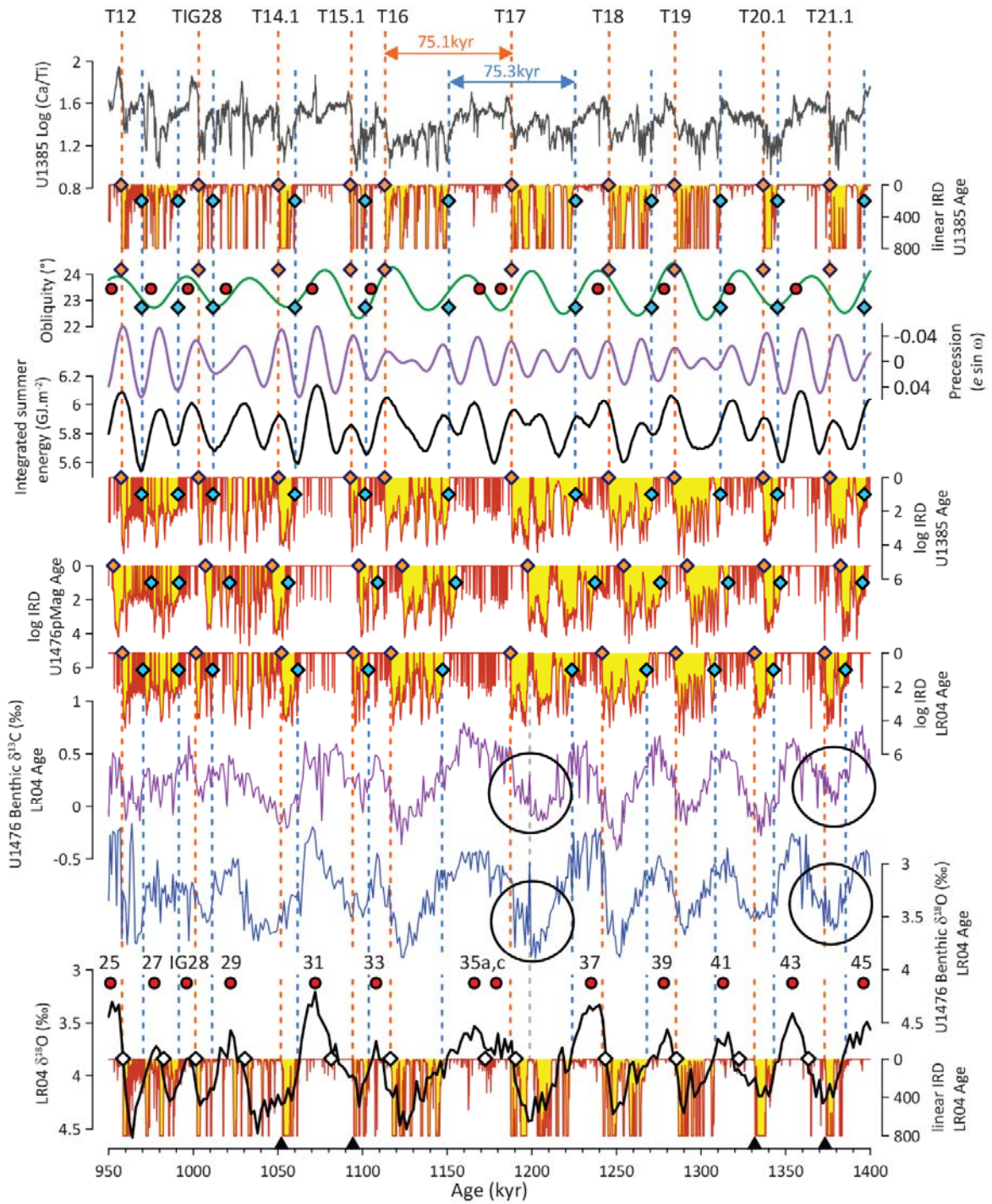


Figure 4. Obliquity loses grip on deglaciation. Throughout: red circles are interglacials (numbered; IG28 is a minimum in $\delta^{18}\text{O}$ associated with MIS 28 (12)), white diamonds are deglacial transitions with respect

to $\delta^{18}\text{O}$ (13), blue diamonds and vertical dashed lines represent onset of significant ice rafting, orange diamonds (and lines) represent end of TIR events. Orange and blue double-headed arrows highlight lengthening of glacial cycles to approximate multiples of the obliquity period following the late occurrence of T17 (see text and also Fig. 3; 1000-1250ka window). From top to bottom: log (Ca/Ti) from U1385 (16), ODP 983 IRD accumulation on linear scale (note cropped scale), obliquity and precession (26), integrated summer energy at 65°N, log IRD from ODP 983 on U1385, U1476pMag and LR04 age models, benthic foraminiferal $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from U1476 on its LR04 age model (13), the LR04 stack (14) and linear IRD on its LR04 age model. Black triangles at bottom highlight 'non-terminating' TIR events (identified as T14.1, T15.1 etc). Large black circles highlight shifts toward lighter values of benthic $\delta^{18}\text{O}$ in U1476 within glacial intervals. Both of these shifts are aligned with coincident features in the records of benthic $\delta^{13}\text{C}$ and IRD. Note our algorithm does not assign a TIR event for T13 because IRD accumulation does not subside sufficiently before MIS 27.

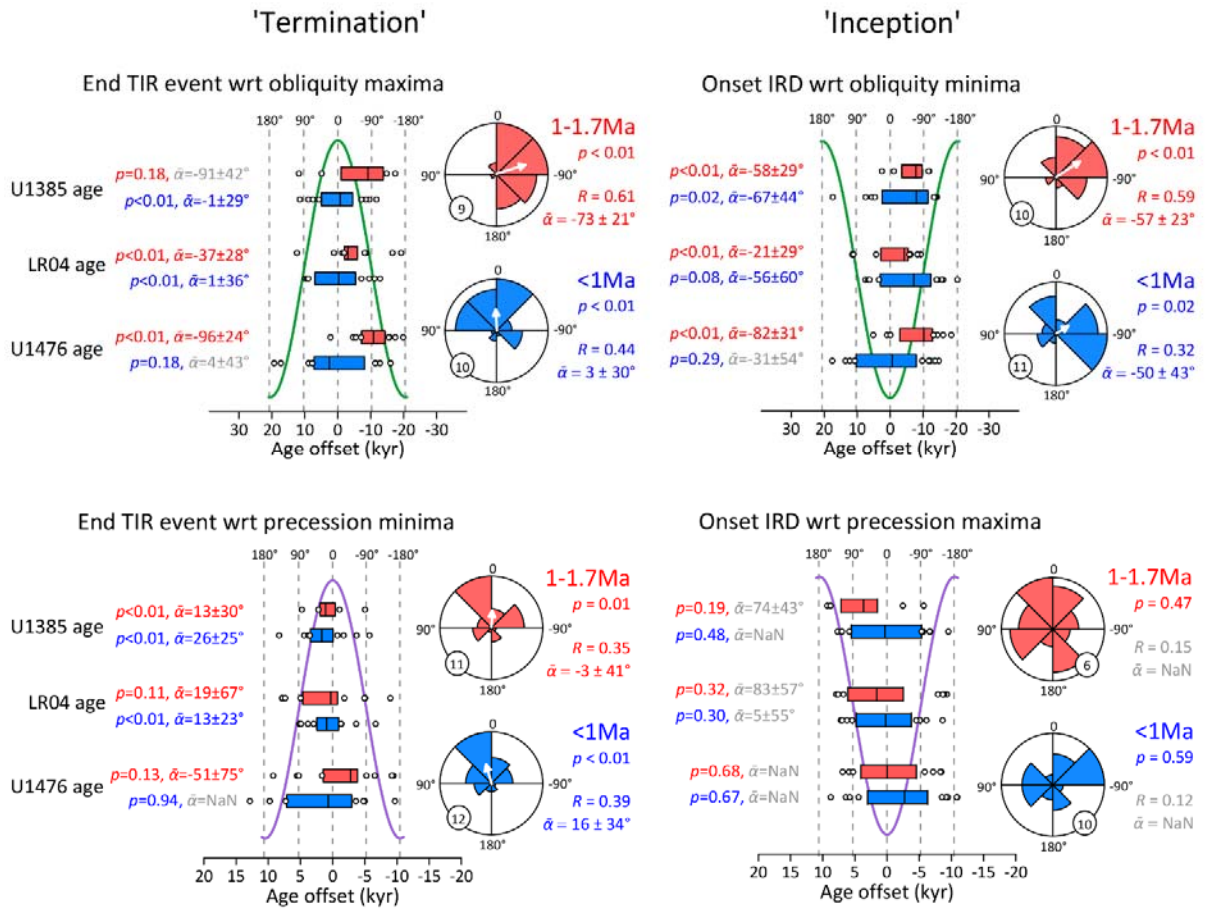


Figure 5. Precession drives terminal ice rafting events throughout last 1.7Myr. Onset (end) of North Atlantic ice rafting across glacial cycles of the past 1.7Myr with respect to insolation minima (maxima) as a function of obliquity and precession (note precession minima imply insolation maxima -and vice versa- in northern hemisphere). All curves represent idealized cycles of obliquity (41kyr period; green) or precession (21kyr period; purple). Box plots for each age model represent median and interquartile range, all other data-points are shown. Red and blue colors represent pre- and post-1Ma. Rose diagrams combine results from the 3 age models (13): Lower values of p suggest higher likelihood of a non-uniform distribution, R is mean resultant vector ($R \rightarrow 1$ as data converge), $\bar{\alpha}$ is mean direction with 95% confidence interval or 80% CI (grey text) for $p > 0.15$ (NaN is returned for $p > 0.4$). Direction of white arrow = $\bar{\alpha}$, length = $R \cdot \text{radial axis}$. Circled number is length of radial axis.

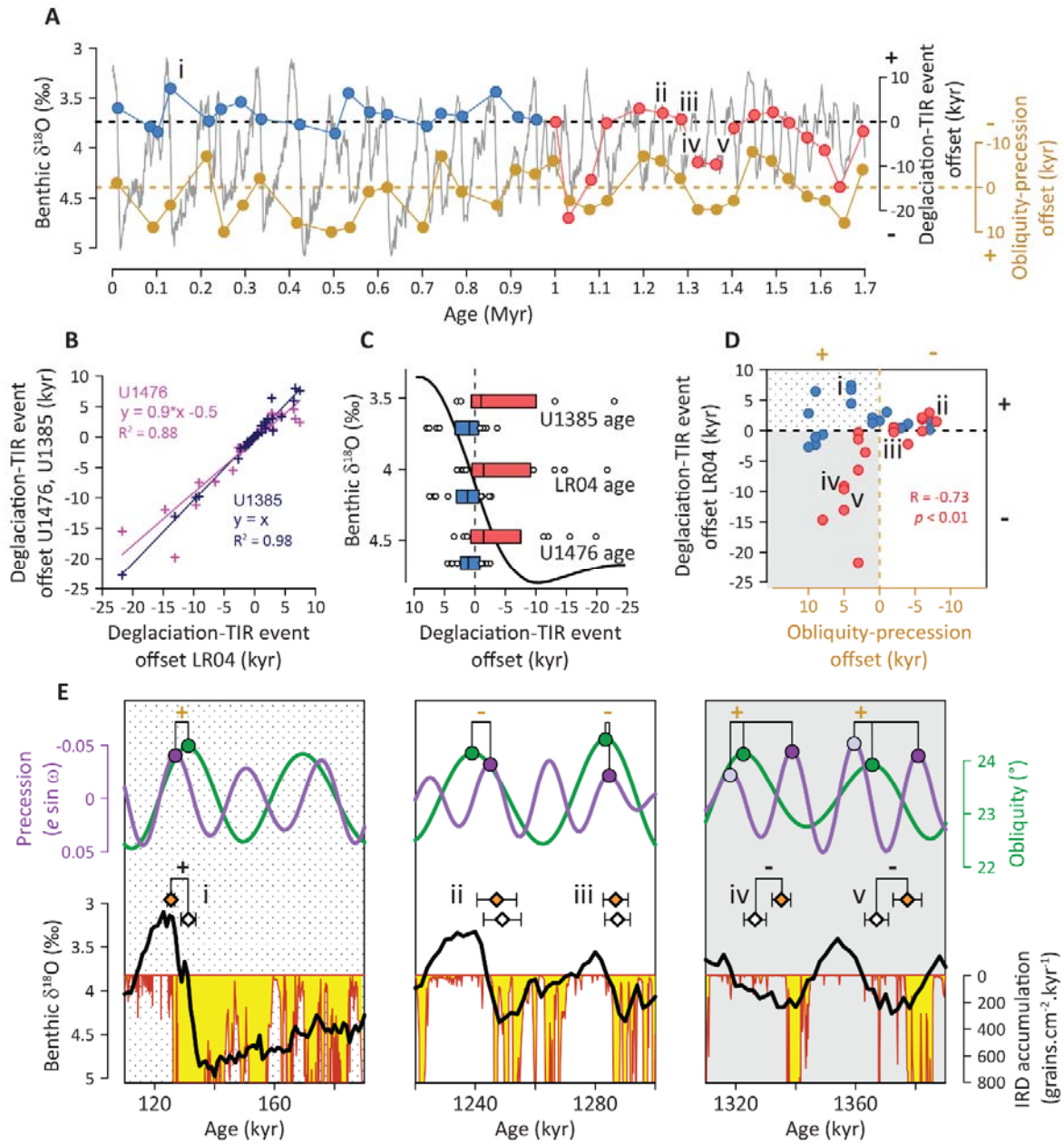


Figure 6. Changing orbits control the relative timing of terminal ice rafting versus deglaciation. (A)

Offsets between the end of TIR events and deglacial transitions as a function of benthic $\delta^{18}\text{O}$ (blue and red circles; a zero offset means that the end of TIR occurs in parallel with the mid-point of deglaciation - defined as the maximum rate of change in $\delta^{18}\text{O}$ (13)- while a negative offset indicates that TIR ends

earlier than the mid-point) compared with offsets between maxima in obliquity and their nearest minima in precession (gold circles; negative offset indicates that the closest precession peak occurs before the peak in obliquity and vice versa). (B) Comparison of the 3 age models for calculating offsets. (C) Box plots representing the calculated offsets before (red) and after (blue) 1Ma. Black curve is the smoothed LR04 stack across Termination 2 for context. (D) Calculated offsets before (red) and after (blue) 1Ma versus the phasing between obliquity and precession (Roman numerals refer to part (A)). For events >1Ma the relationship is significant ($p < 0.005$, $R = -0.73$) (13). (E) Examples of the various phasing between obliquity and precession shown in (D) and associated offsets between TIR events and deglaciation. Orange diamonds represent the end of TIR events, white diamonds are deglacial transitions (each data point represents the mean of the 3 age model results $\pm 1\sigma$).

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Supplementary Materials for

Persistent influence of precession on northern ice sheet variability since the early Pleistocene

Stephen Barker, Aidan Starr, Jeroen van der Lubbe, Alice Doughty, Gregor Knorr, Stephen Conn, Sian Lordsmith, Lindsey Owen, Alexandra Nederbragt, Sidney Hemming, Ian Hall, Leah Levay and the IODP Exp 361 Shipboard Scientific Party

Correspondence to: barkers3@cf.ac.uk

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30

31 Hall, I.R.¹, Hemming, S.R.², LeVay, L.J.³, Barker, S.¹, Berke, M.A.⁴, Brentegani, L.⁵, Caley, T.⁶,
 32 Cartagena-Sierra, A.⁴, Charles, C.D.⁷, Coenen, J.J.⁸, Crespin, J.G.⁶, Franzese, A.M.⁹, Gruetzner,
 33 J.¹⁰, Han, X.¹¹, Hines, S.K.V.¹², Jimenez Espejo, F.J.¹³, Just, J.¹⁴, Koutsodendris, A.¹⁵, Kubota,
 34 K.¹⁶, Lathika, N.¹⁷, Norris, R.D.⁷, Periera dos Santos, T.¹⁸, Robinson, R.¹⁹, Rolison, J.M.²⁰,
 35 Simon, M.H.²¹, Tangunan, D.¹, van der Lubbe, H.J.L.²², Yamane, M.²³, and Zhang, H.²⁴.

36

37 ¹School of Earth and Environmental Sciences, Cardiff University, UK. ²Lamont-Doherty Earth
 38 Observatory, Columbia University, USA. ³International Ocean Discovery Program, Texas A&M
 39 University, USA. ⁴Department of Civil Engineering & Geological Sciences, University of Notre
 40 Dame, USA. ⁵Earth and Environmental Sciences, University of Technology Queensland,
 41 Australia. ⁶EPOC, UMR CNRS 5805, University of Bordeaux, France. ⁷Scripps Institution of
 42 Oceanography, University of California, USA. ⁸Department of Geology, Northern Illinois
 43 University, USA. ⁹School of Earth and Environmental Sciences, Hostos Community College
 44 (CUNY), USA. ¹⁰Geosciences, Alfred-Wegener-Institut for Polar and Marine Research,
 45 Germany. ¹¹Second Institute of Oceanography, Key Laboratory of Submarine Science, China.
 46 ¹²Woods Hole Oceanographic Institution, Woods Hole, USA. ¹³Institute of Biogeosciences,
 47 Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan. ¹⁴Geologisches
 48 Institut, Universität Köln, Germany. ¹⁵Institute of Earth Sciences, University of Heidelberg,
 49 Germany. ¹⁶Atmosphere and Ocean Research Institute, University of Tokyo, Japan. ¹⁷National
 50 Centre for Polar and Ocean Research, Ministry of Earth Sciences, Goa, India. ¹⁸Institute for
 51 Geosciences, Universidade Federal Fluminense (UFF), Brazil. ¹⁹Graduate School of
 52 Oceanography, University of Rhode Island, USA. ²⁰Lawrence Livermore National Laboratory,
 53 USA. ²¹NORCE, Bergen, Norway. ²²Department of Earth Sciences, Vrije Universiteit
 54 Amsterdam, Netherlands. ²³Institute for Space-Earth Environmental Research, Nagoya
 55 University, Japan. ²⁴School of Ecology and Environmental Science, Yunnan University, China

56

57 Materials and Methods

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59 Sample preparation

60 For this study we processed 1,857 samples along the splice of ODP 983 (27) and 2,366
 61 samples along the splice of IODP U1476 (28) (Fig. S1). Sediment samples were spun overnight
 62 and washed with DI water through a 63µm sieve before being dried at 40°C. IRD counts from
 63 Site 983 were made on the >150µm fraction after splitting to yield approximately 300 entities
 64 following previous studies (10, 29, 30). IRD was considered as the total number of
 65 lithogenic/terrigenous grains counted. Benthic foraminiferal stable isotopes from Site U1476
 66 were performed on *Cibicidoides wuellerstorfi* (ideally 3 individuals) picked from the 250-355µm
 67 fraction (occasionally >355µm) and measured at Cardiff University using a Thermo Finnigan
 68 MAT 253 mass spectrometer linked online to a Carbo Kiel carbonate preparation device. Long-
 69 term precision is ±0.05‰ for δ¹⁸O and ±0.021‰ for δ¹³C (±1σ). Results are calibrated to an
 70 internal laboratory standard (BCT63) and presented relative to the Vienna Pee Dee Belemnite
 71 scale. The records from U1476 presented here have an average temporal resolution of 840 years

72 and span the interval ~1.8Ma to present. A lower resolution subset of the $\delta^{18}\text{O}$ dataset (every 4th
 73 sample) was presented recently by van der Lubbe *et al.* (31).

74

75 Age model development

76 ODP Site 983 is part of the LR04 benthic $\delta^{18}\text{O}$ stack (14) and we are therefore able to use
 77 its corresponding (LR04) age model as one of our timescales (Fig. S2c). We also developed an
 78 ‘LR04’ age model for Site U1476 by tuning its record of benthic $\delta^{18}\text{O}$ to LR04 (Fig. S2b). We
 79 used a limited number of tie points (34 over the last 1.7Myr) to avoid over-tuning, which we
 80 suggest provides a more objective approach when testing for the presence of orbital frequencies.
 81 Even with this limited number of tuning points we observe an excellent correlation between our
 82 new benthic $\delta^{18}\text{O}$ record and LR04 ($\delta^{18}\text{O}_{\text{U1476}} + 0.64 = 1.003 * \delta^{18}\text{O}_{\text{LR04}}$ $R^2 = 0.998$), which implies
 83 that the site of U1476 reflects reasonably well the global ‘average’ ocean composition, at least
 84 with respect to $\delta^{18}\text{O}$.

85

86 Next we develop an absolute age model for ODP 983 based on the growing body of
 87 $^{40}\text{Ar}/^{39}\text{Ar}$ -dated magnetic polarity reversals and magnetic excursions (15, 32):

88

89 Step (1): ODP Site 983 has excellent records of relative geomagnetic paleointensity (it is
 90 part of the PISO-1500 stack (33)) and inclination (27, 34, 35) (Fig. S2e, f), which makes it an
 91 ideal candidate for developing an absolute age scale through this approach. We therefore use a
 92 recent compilation (15) of $^{40}\text{Ar}/^{39}\text{Ar}$ dates from volcanic sequences to assign absolute ages to
 93 ODP 983 (Table S1). In order to standardize the assignment of ages we identify minima in
 94 paleomagnetic intensity (as described by Channell *et al.* (15) and depicted in their Figs. 1, 4, 5,
 95 8) and/or transitions in inclination at Site ODP983 associated with $^{40}\text{Ar}/^{39}\text{Ar}$ dated horizons (15).
 96 Symmetrical depth uncertainties are calculated as the width of the corresponding minima
 97 (intensity) or transition (inclination). An initial absolute age model for ODP 983 (pMag) was
 98 constructed by linear interpolation between these points and is illustrated in Figure S2e-g.

99

100 Step (2): Sediment accumulation rates at ODP Site 983 are sensitive to the overflows of
 101 deep water crossing the Iceland-Scotland Ridge (10) and are highly variable (Fig. S2k).
 102 Sedimentation rates at Site U1476 are less variable (Fig. S2j) due to its location away from major
 103 bottom currents. However, the shipboard paleomagnetic data obtained for U1476 were heavily
 104 overprinted (36, 37) and could not be used to develop an absolute paleomagnetic timescale
 105 directly. We therefore transfer the Ar/Ar ages from Site 983 (Table S1) to the U1476 depth scale
 106 by graphically aligning the benthic $\delta^{18}\text{O}$ records of both sites. To correlate two signals in this
 107 manner, it is preferable to identify intervals of high rate of change (i.e. transitions in the $\delta^{18}\text{O}$
 108 record), however the Ar/Ar ages assigned to ODP983 do not always align with recognizable
 109 transitions in the $\delta^{18}\text{O}$ record (Fig. S2g, h). Therefore, we chose to align the nearest recognizable
 110 $\delta^{18}\text{O}$ transitions preceding and succeeding each Ar/Ar age with the corresponding transitions in
 111 U1476, before using linear interpolation to transfer the age onto the U1476 depth scale. We then
 112 take the distance from this point to the nearest transition as the 3 sigma U1476 depth uncertainty
 113 for this point; assuming that the Ar/Ar age must fall between the two transitions. The result of
 114 this step is a set of Ar/Ar ages (with uncertainties) and the corresponding depths in U1476, also
 115 with uncertainties (Table S1).

116

117 Step (3): Next, we input the U1476 age-depth tie points from step 2 into the deterministic
 118 age-depth modelling software “Undatable” (38) using an “x-factor” of 0.5 and 10^5 iterations.
 119 To ensure that the paleomagnetic tie points are constrained we do not include them in the
 120 bootstrapping routine. The result is the “U1476pMag” age model for U1476 with age uncertainty
 121 estimates (Figs. S2, S3). As shown in Fig. S3a, c, the uncertainty estimates for the U1476pMag
 122 age model are typically large (mean ~ 16 kyr 1σ), increasing up to 40kyr at ~ 1.5 Ma where age
 123 control points are particularly sparse. On the other hand the offset between our absolute
 124 (U1476pMag) age model for U1476 and that derived by tuning to LR04 is generally much
 125 smaller than the age uncertainty estimates for U1476pMag, averaging 6.6kyr (in absolute terms)
 126 over the last 1.8Myr (Fig. S3b, d). We suggest that our final U1476pMag age model with its
 127 corresponding record of benthic $\delta^{18}\text{O}$ (Fig. S2h) might become a standard absolute reference
 128 timescale (spanning the last ~ 1.8 Myr) for future studies.

129
 130 Step (4): Finally, the absolute age model U1476pMag was transferred back to ODP 983 by
 131 further tuning between their records of benthic $\delta^{18}\text{O}$ (Fig. S2i). Note that the final absolute age
 132 model for ODP Site 983 (U1476pMag) includes the initial constraints obtained in step (1) above.
 133

134 A third age model for ODP Site 983 was constructed by tuning to the reference timescale
 135 published for IODP Site U1385 (16). Following our previous study (12) we tuned our records
 136 from ODP Site 983 to the U1385 record of log Ca/Ti acquired by XRF scanning (16) (Fig. S4).
 137 At the site of U1385 log(Ca/Ti) is thought to reflect changes in the relative supply of biogenic
 138 carbonate and detrital sediment. Biogenic carbonate apparently increases during interglacial and
 139 interstadial periods and decreases during glacial and stadial periods and therefore provides a
 140 proxy for high northern latitude millennial-scale climate variability. For the interval 1.2-1.7Ma
 141 we limited our tuning to features in the IRD and coarse fraction records. Details for the interval
 142 0-1.2Ma were reported previously (12). Hodell et al. (16) derived several age models for U1385
 143 but here we employ that obtained by correlating peaks in L^* (i.e. sediment colour) to local
 144 summer insolation at 37°N , based on the observation of a strong precession-like signal within L^*
 145 that displays similar amplitude modulation as precession (a function of eccentricity).
 146

147 The final timeseries of IRD accumulation and IRD grains per gram versus core depth are
 148 shown in Figure S5.

149 IRD accumulation rates

150 IRD accumulation rates were calculated from IRD/g and dry bulk accumulation rates,
 151 obtained by combining linear sedimentation rates with an estimate for dry bulk density. Dry bulk
 152 density was derived from continuous GRAPE density measurements calibrated with discrete
 153 (index property) measurements of wet and dry bulk density (27) according to equation (1):
 154

$$155 \text{ Dry Bulk Density} = (\text{GRAPE} + 0.17) * 1.5547 - 1.5719 \quad (1)$$

156 Linear IRD versus log IRD

157 In general the largest peaks in IRD accumulation are associated with deglacial intervals
 158 (Fig. S6). This is most apparent when IRD is plotted on a linear scale and results in an apparent
 159 time lag (on G-IG timescales) between LR04 (14) and IRD accumulation (which is plotted here
 160 on its LR04 age model). However, no lag is observed between the LR04 stack and log IRD (Fig.
 161
 162

163 S6). This is because taking the log of IRD accumulation (+1) enhances variability when IRD
164 accumulation is low to moderate, which we argue highlights the fact that ice rafting occurs
165 (albeit at relatively low levels) whenever ice sheets are large enough to experience marine
166 calving. By extension it follows that our record of log IRD accumulation reflects the growth
167 (extension) and decay (retraction) of circum-NE Atlantic ice sheets relatively closely (compared
168 to linear IRD) and that this growth and decay in turn mirrors (at low frequencies) variations in
169 the LR04 stack. The corollary of this is that in general the LR04 stack mirrors variations in
170 northern ice sheet variability.

171

172 Algorithm to determine the start end of significant ice rafting

173 We wish to assess the timing of ice rafting events with respect to orbital parameters and
174 changing sea level (in this case the LR04 stack). Initially, interglacial (IG) events are identified
175 by picking minima in the LR04 benthic $\delta^{18}\text{O}$ record after applying a 10kyr smooth, which
176 minimizes the number of un-named warm stages while preserving most of the named interglacial
177 stages (39) (Fig. S7). We also impose a maximum absolute value of 4.25‰ to avoid picking
178 minima during glacial intervals. Deglacial transitions in LR04 are identified as minima in the
179 smoothed first time-differential of the smoothed record of LR04 (Fig. S8).

180

181 To assess the start and end of significant ice rafting in the IRD record from ODP 983 we
182 develop an ‘IRD index’ which discriminates between intervals of high and low IRD
183 accumulation. We first apply a 13-point running mean (implemented via `filtfilt` in Matlab i.e. run
184 forwards and backwards) to the record of log IRD before detrending to account for the generally
185 higher concentrations of IRD in more recent sediments (by subtraction of a linear ramp from 0 to
186 0.5 over the 1.7Myr record; Fig. S9). Our next step is to choose a threshold above which we
187 consider ice rafting significant. We find that a value of $\log \text{IRD} = 1.3$ (equivalent to $20 \text{ grains.cm}^{-2} \cdot \text{kyr}^{-1}$)
188 is successful at delineating between relatively icy versus ice-free conditions throughout
189 the whole 1.7Myr record (Fig. S8, S9). Each sample interval is then assigned a value
190 representing either high or low IRD to generate the IRD index (Fig. S8, S9).

191

192 To identify the onset of significant ice rafting the algorithm searches for the first transition
193 to high IRD following each interglacial. A similar procedure is used to identify the end of ice
194 rafting prior each interglacial, with the additional constraint that the preceding interval of high
195 IRD must be at least 2.8kyr in duration. This is because we are interested in the major IRD
196 events associated with glacial terminations in the late Pleistocene (here termed TIR events).
197 Temporal offsets between the onset and end of (terminal) ice rafting versus minima and maxima
198 in obliquity and precession (Fig. 5) are then obtained by identifying the nearest orbital peak to
199 each event of interest and differencing their respective ages. The algorithm was optimized (see
200 below) using the LR04 age model and ages for each transition in IRD were transferred to the
201 other age models via their respective depth in core. Note though that the closest orbital peaks in
202 each case are allocated independently i.e. a different peak might be assigned for the same
203 transition in IRD depending on the age model employed.

204

205 The observed relationship between the end of a TIR event and deglaciation versus the
206 obliquity-precession offset for events $>1\text{Ma}$, as shown in Fig. 6D, was assessed using the
207 surrogateCor function in *Astrochron* (22) and is found to be significant: $R = -0.73$, $p < 0.005$
208 (based on 2000 phase-randomized surrogate series in the Monte Carlo simulation).

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In Figure S10 we show an analysis to demonstrate the sensitivity of the algorithm to the various parameter values assigned (using the LR04 age model). Our parameter choices were made in order to maximize the number of TIR events identified where possible. As can be seen, the main conclusions of our study are insensitive to a wide range of parameter values. The parameter with the most substantial influence on the results is the threshold used to discriminate between low and high IRD levels. Use of a very low threshold (e.g. 0.5) means that the end of a TIR event will necessarily occur relatively close to the respective IG event irrespective of when the major episode of deglacial ice rafting ends (as discriminated by eye) because a certain amount of ice rafting continues during the early stages of most interglacials. Since the LR04 age model is orbitally tuned, this results in a rather monotonous temporal relationship observed between the end of TIR events (according to the algorithm with low threshold) and the phase of obliquity and precession. Use of a low threshold also reduces the number of TIR events identified in the <1Ma portion of the record because of the generally higher fluxes of IRD at these times (a TIR event cannot be detected if ice rafting continues throughout the associated IG).

Temporal offsets between deglaciations and maxima in obliquity are obtained by identifying the closest obliquity peaks to each deglacial transition and differencing (Fig. S11). Since the record of benthic $\delta^{18}\text{O}$ from ODP Site 983 is part of the LR04 stack (14), we can transfer the ages of deglacial transitions in LR04 onto the other age models developed for ODP Site 983. This is done by transferring the age of each deglacial transition in the LR04 stack into the depth domain of 983 using the LR04 age model published by ref (14). Each depth is then assigned ages on the U1476pmag or U1385 age models described above. Figure S11 reveals the close correspondence observed between deglaciations and rising to maximum obliquity throughout the last 1.7Myr for all three age models employed here.

Circular statistics

Circular statistics shown in Figs. 5 and S11 were calculated using the CircStat toolbox for MATLAB developed by Berens (40). Below we summarize the various functions employed here:

Rayleigh test for a unimodal deviation from uniformity tests the null hypothesis (H_0) that the population is distributed uniformly around the circle. The approximate p-value under H_0 is computed as:

$$p = \exp\left[\sqrt{(1 + 4N + 4(N^2 - R_n^2))} - (1 + 2N)\right]$$

where $R_n = R \cdot N$ (see below for definition of R). The lower the value of p , the greater the likelihood that H_0 can be rejected.

Mean angle ($\bar{\alpha}$). Individual directions are first transformed to unit vectors in the 2-D plane:

$$r_i = \begin{pmatrix} \cos \alpha_i \\ \sin \alpha_i \end{pmatrix}$$

254
255 The vectors r_i are then vector averaged:

$$256 \quad \bar{r} = \frac{1}{N} \sum_i r_i$$

257 where \bar{r} is the mean resultant vector. To yield the mean angular direction $\bar{\alpha}$, \bar{r} is transformed
258 using the four quadrant inverse tangent function (40).

259
260 **Resultant vector length (R):**

$$261 \quad R = \|\bar{r}\|$$

262
263 R varies between 0 and 1 with R closer to 1 if the data are more concentrated around the mean
264 direction.

265
266 **Confidence Intervals for the Mean Direction.** The $(1-\delta)\%$ -confidence intervals for the
267 population mean are computed for $R \leq 0.9$ and $R > \sqrt{\chi_{\delta,1}^2/2N}$ using:

$$268 \quad d = \arccos \left[\frac{\sqrt{\frac{2N(2R_n^2 - N\chi_{\delta,1}^2)}{4N - \chi_{\delta,1}^2}}}{R_n} \right]$$

269
270
271 where $R_n = R \cdot N$ and for $R > 0.9$ using:

$$272 \quad d = \arccos \left[\frac{\sqrt{N - (N^2 - R_n^2) \exp(\chi_{\delta,1}^2/N)}}{R_n} \right]$$

273
274
275 In both cases, the lower confidence limit of the mean, $L_1 = \bar{\alpha} - d$ and the upper confidence limit,
276 $L_2 = \bar{\alpha} + d$.

277
278 In order to benefit from the use of multiple age models we combine the results from the 3
279 age models as follows: Firstly, because the LR04 and U1385 age models are both based on
280 orbital tuning, they are not truly independent. We therefore take the mean age for each IRD
281 transition using these 2 age models before applying the algorithm to search for the nearest orbital
282 peaks. We then combine these results with those from the U1476pmag age model before
283 implementing CircStat. By this combination we are weighting orbital and non-orbital age
284 modelling methods equally.

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289 Frequency analysis

290 All frequency analyses were performed on evenly resampled (200yr for logIRD and 1kyr
 291 for the LR04 stack and the benthic $\delta^{18}\text{O}$ record from U1476) timeseries. Bandpass filtering was
 292 performed using a Taner filter (roll-off rate = 10^4) within the Astrochron (22) Package for R
 293 (41). For spectral analyses we employed the ‘robust’ (multi-taper spectral analysis with median
 294 smoothing of the spectrum to estimate the underlying noise background) AR(1) method of (17)
 295 (updated by (18)) and an alternative spectral noise estimation method (LOWSPEC (18)) which is
 296 designed to overcome some of the problems associated with the AR1 method (including inflated
 297 confidence level estimates and excessive clumping of false positives within the low frequency
 298 portion of the spectrum). LOWSPEC simultaneously allows for departures from the AR(1)
 299 assumption, and is more able to accurately identify astronomical signals when they are present in
 300 the data (18). The power spectra and estimated red noise models for each analysis are shown in
 301 Fig. S12-14.

302
 303 We also apply an MTM Harmonic F-test, designed to test for phase-coherent sinusoids in
 304 white or colored noise (18, 42, 43) and which is quasi-independent of the other tests we apply.
 305 Following the procedure outlined by (18) and implemented in the Astrochron package for R (22),
 306 an F-test peak is reported if it achieves the specified MTM harmonic confidence level (>90%)
 307 while also achieving the specified robust red noise or LOWSPEC confidence level \pm half the
 308 power spectrum bandwidth resolution. In addition, significant F-tests must occur on a local
 309 power spectrum high, which is parameterized as occurring above the local LOWSPEC or robust
 310 red noise background estimate. We note that although the F-test confidence is relatively high for
 311 peaks within the precession band of the 1250-1700ka interval of logIRD record (Fig. S15), none
 312 of these peaks pass the test criteria outlined above.

313
 314 Wavelet transforms and cross wavelet transforms (Figs. S16, S17) were produced using the
 315 Matlab functions presented by Grinsted and Moore (44), implemented on evenly resampled
 316 (200yr for logIRD and 1kyr for the LR04 stack and $\delta^{18}\text{O}$ from U1476; 1kyr resampling was used
 317 for both logIRD and LR04 in the cross wavelet transform) timeseries. Note that the significance
 318 level within cross wavelet transform may be overestimated as a result of strong power within
 319 either of the individual wavelets (45).

320
321 Insolation metrics

322 Calculations for determining the insolation metrics shown in Figure 1 were based on the
 323 Palinsol (46) package for R, using the astronomical solutions of Laskar (47).

324
325 **Supplementary References**

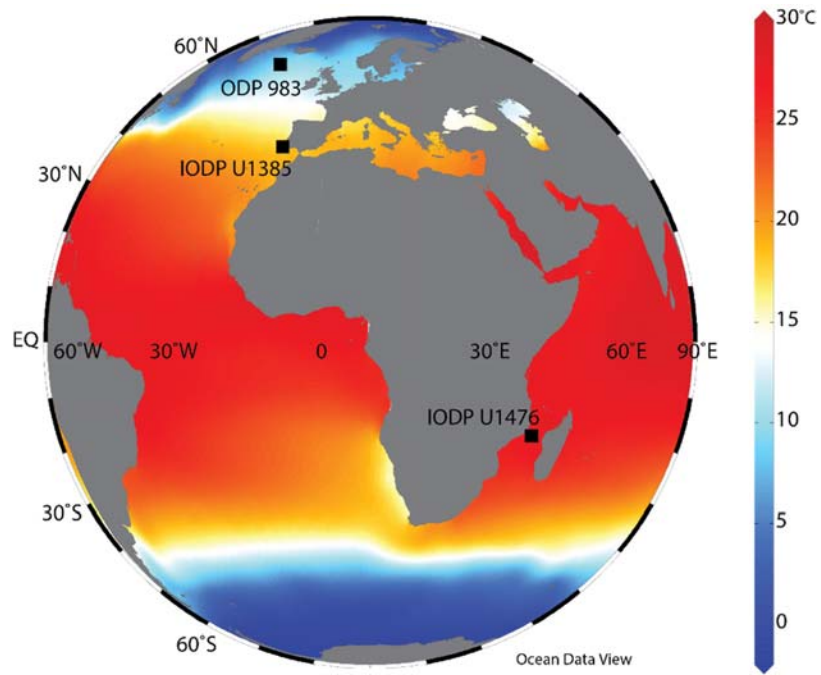
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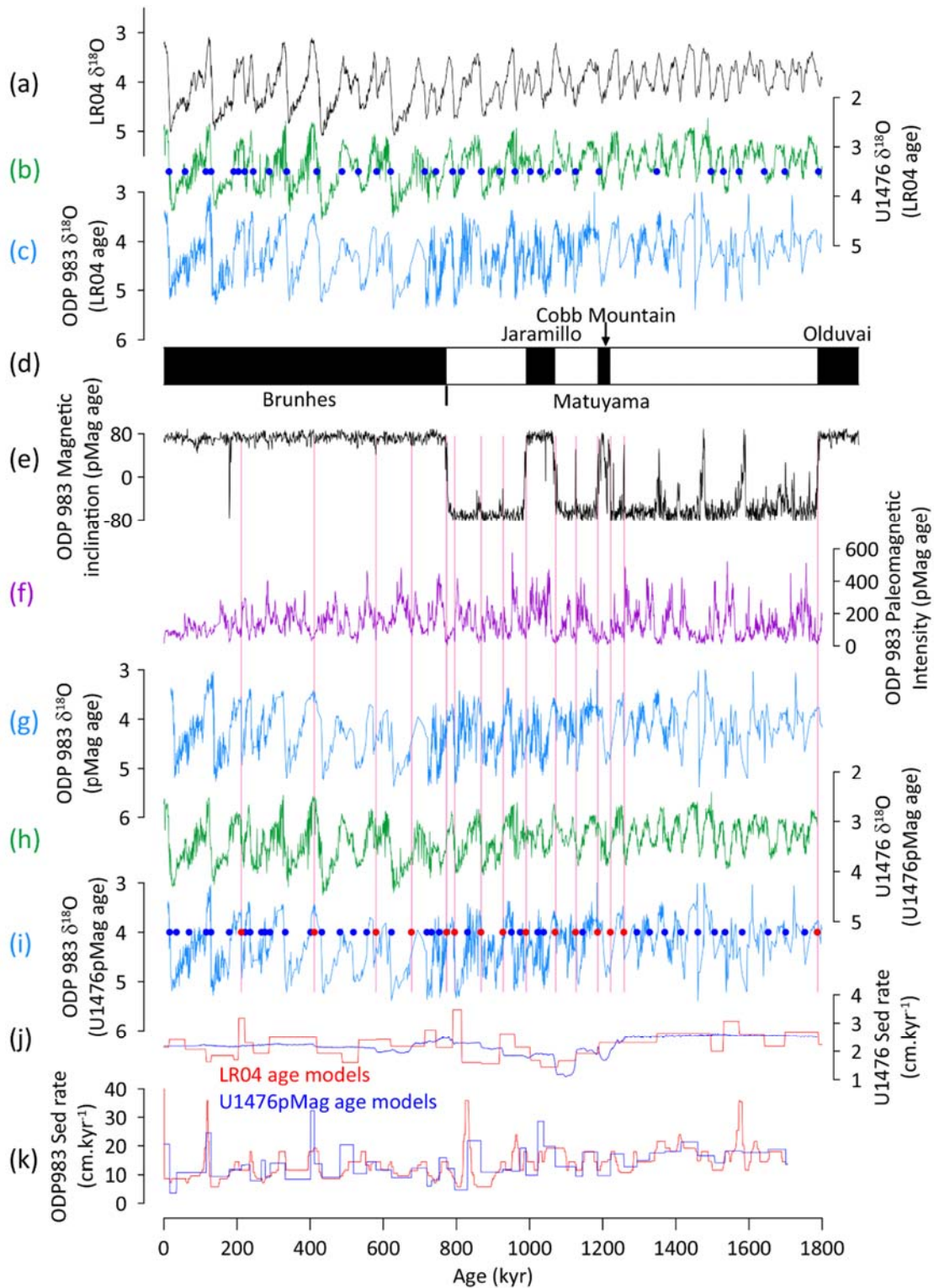


393

394 **Fig. S1.**

395 Locations of Sites 983, U1385 and U1476 plotted with annual sea surface temperature (48).

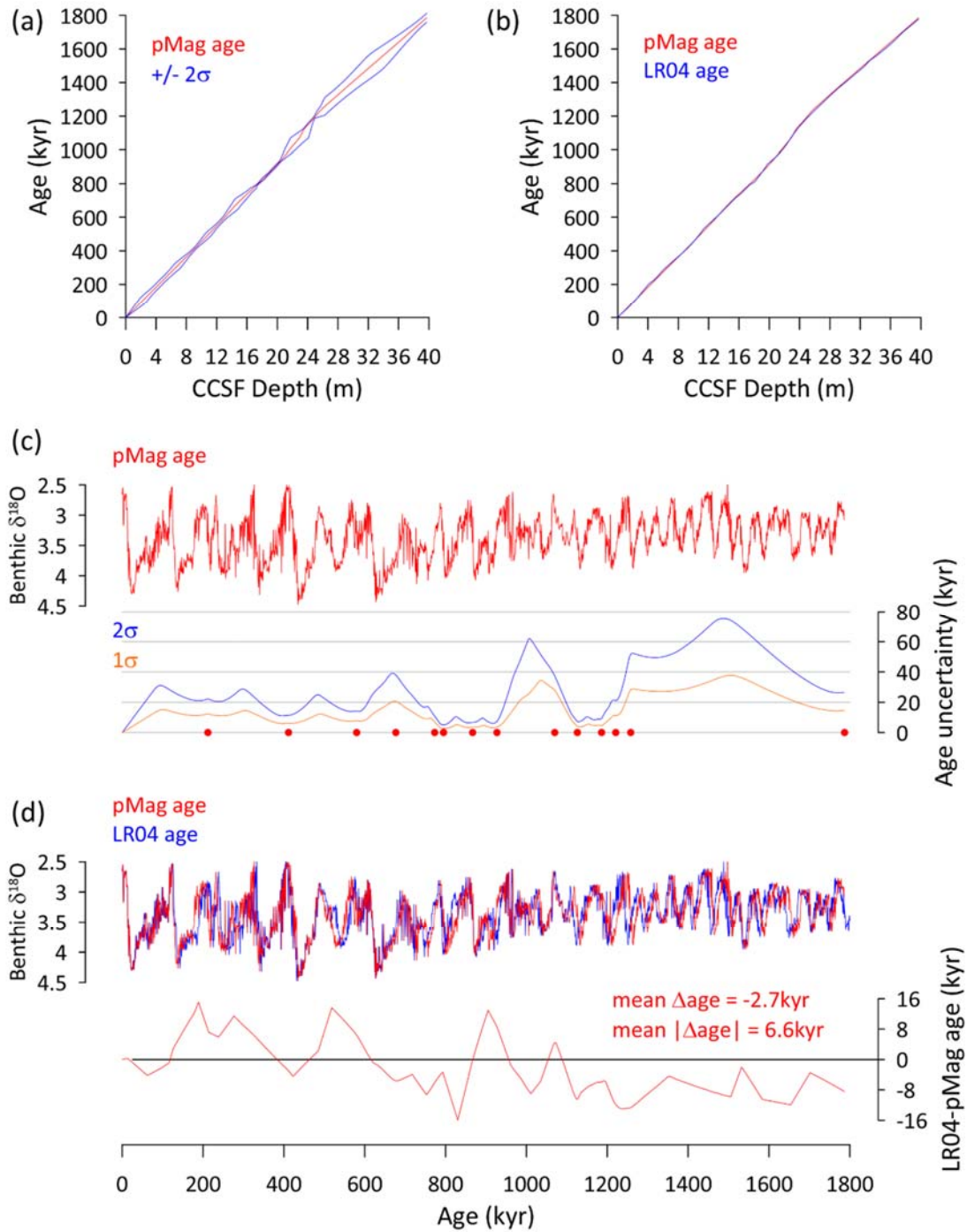
396



397 **Fig. S2.**

398 Development of absolute timescales for ODP 983 and U1476 and LR04 timescale for U1476. (a)
 399 The LR04 stack (14) was used as a tuning target for the benthic $\delta^{18}\text{O}$ record of U1476 to derive

400 the LR04 age model for this site (b; blue circles are tuning points). (c) We use the published
401 LR04 age model for ODP Site 983 as one of our timescales. (d) Major paleomagnetic chrons,
402 sub-chrons and excursions of the past 1.8Myr. Records of magnetic inclination (e) and
403 paleomagnetic intensity (f) from ODP 983 (27, 34, 35) on the initial (pMag) absolute timescale
404 derived from Table S1 (vertical red lines are absolute age constraints). (g) the benthic $\delta^{18}\text{O}$
405 record from ODP 983 (34, 49, 50) on its initial absolute age model (pMag) is used to transfer
406 absolute constraints onto U1476 to derive the final absolute timescale, U1476pMag. (h) the
407 benthic $\delta^{18}\text{O}$ record from U1476 (U1476pMag age) is then used as a tuning target for ODP 983
408 to derive the U1476pMag age model for this site (i). Blue circles in part (i) are additional
409 constraints from tuning to U1476 benthic $\delta^{18}\text{O}$ on the U1476pMag timescale. (j, k)
410 sedimentation rates for the 2 sites on their LR04 and U1476pMag age models.
411



412

413 **Fig. S3.**

414 U1476pMag versus LR04 age models for U1476. (a) U1476pMag age vs depth with $\pm 2\sigma$ plotted.

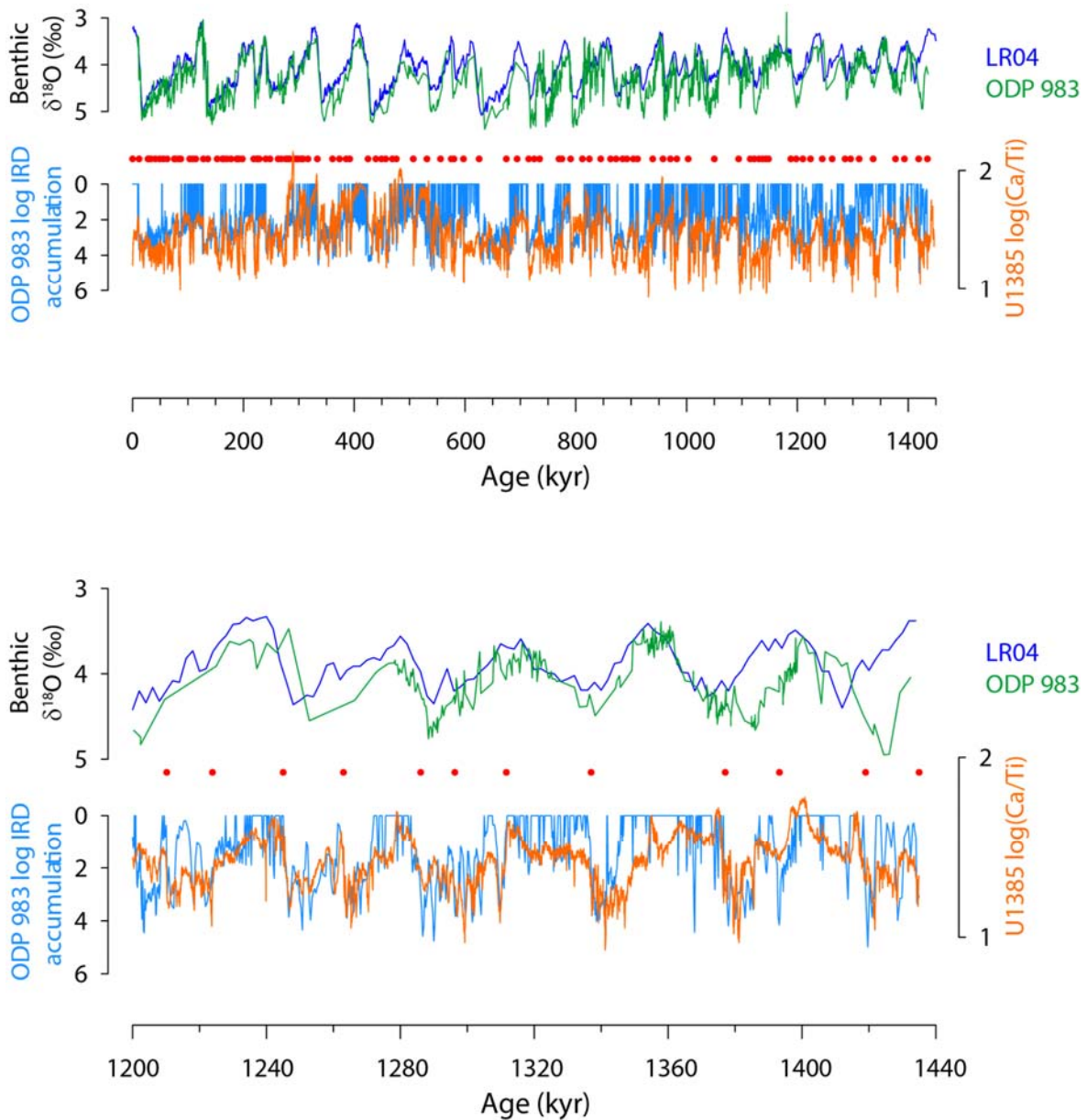
415 (b) U1476pMag and LR04 age vs depth. (c) Benthic $\delta^{18}\text{O}$ from U1476 plotted on its U1476pMag

416 age model with age uncertainties versus time (red circles are age control points; Table S1). (d)

417 Benthic $\delta^{18}\text{O}$ from U1476 on its U1476pMag and LR04 age models with the age offset plotted

418 versus time.

419



420

421

Fig. S4.

422 Construction of the U1385 age model for ODP Site 983. Upper panel shows whole record (the

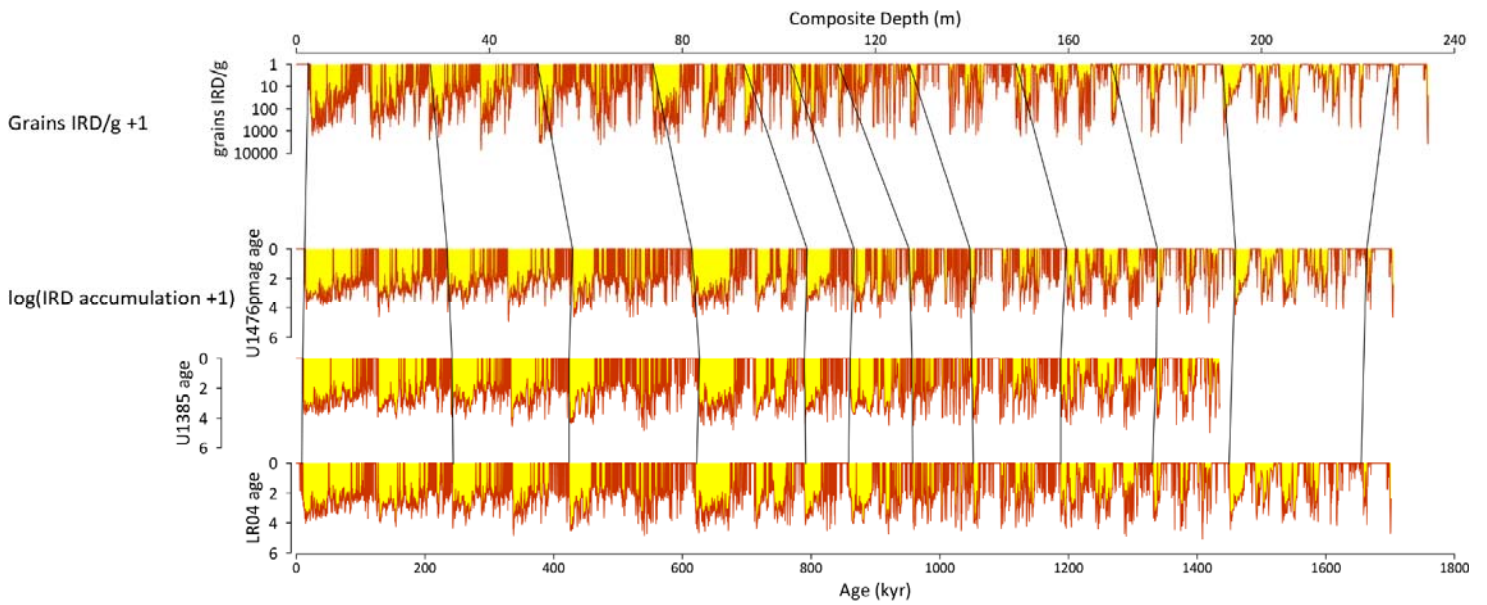
423 U1385 age scale (16) does not extend beyond 1450ka). Lower panel shows the portion

424 developed here (earlier portion was presented previously (12)). In both panels the benthic $\delta^{18}\text{O}$

425 record from ODP 983 (34, 49, 50) is plotted on the U1385 age model and compared with the

426 LR04 stack on its own timescale. Red circles are tuning points.

427



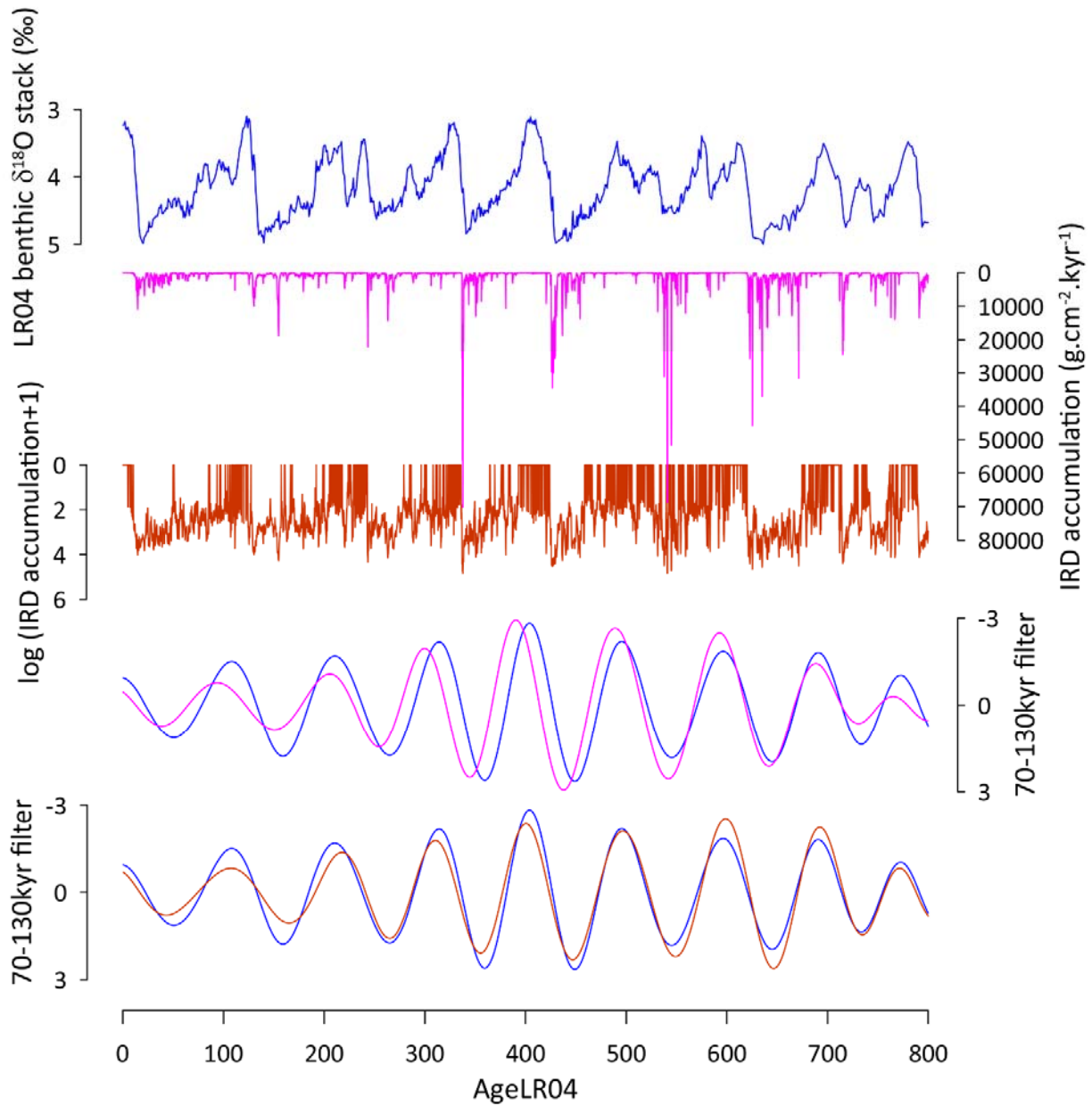
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430 **Fig. S5.**

431 Record of IRD grains per gram versus core depth in ODP 983 along with timeseries of IRD
432 accumulation on the 3 age models developed here. Tie-lines are for illustrative purposes only.

433

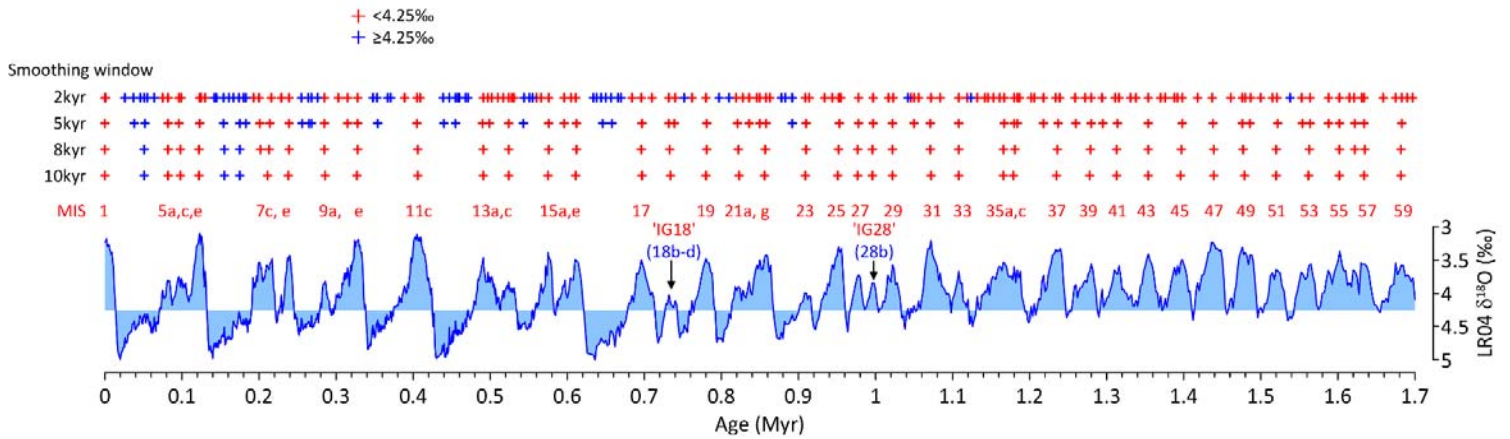


434

435 **Fig. S6.**

436 Use of log IRD reduces the skew towards deglacial ice rafting events and reveals an in-phase
 437 relationship between ice rafting and sea level (LR04) on G-IG timescales. All blue curves
 438 represent the LR04 stack, magenta curves are linear IRD and red curves are log IRD.

439



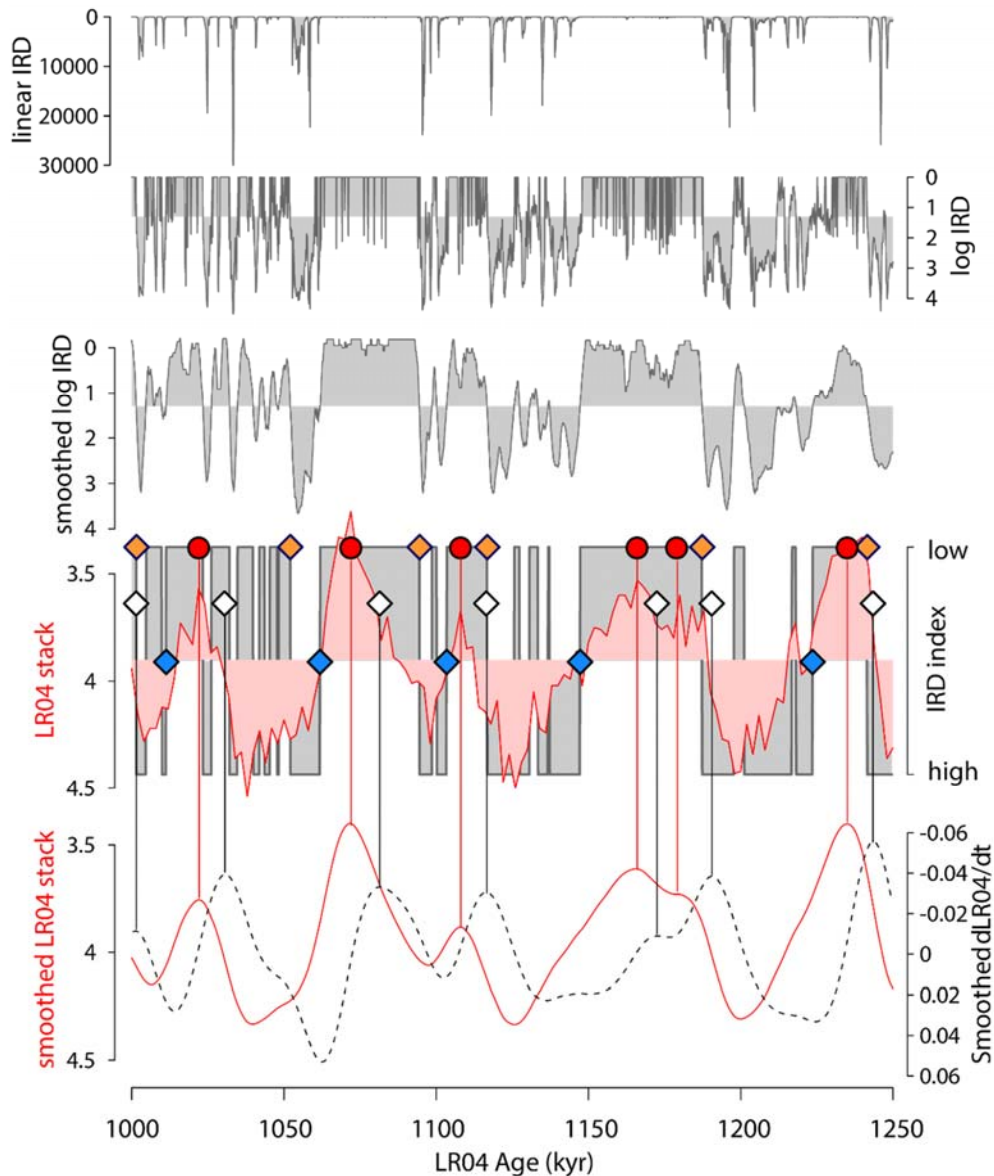
440

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442 **Fig. S7.**

443 Interglacial (IG) events (red crosses) identified as minima in the LR04 benthic $\delta^{18}\text{O}$ stack using
 444 various smoothing windows. IG18 and IG28 (12) are conspicuous minima that have previously
 445 been associated with glacial stages 18b-d and 28b respectively (39). They are included here
 446 because of their conspicuous nature and in order to preserve and include MIS 23. Blue crosses
 447 are ‘glacial’ $\delta^{18}\text{O}$ minima (e.g. within MIS 3 and 6) that are excluded by use of a maximum
 448 threshold of 4.25‰.

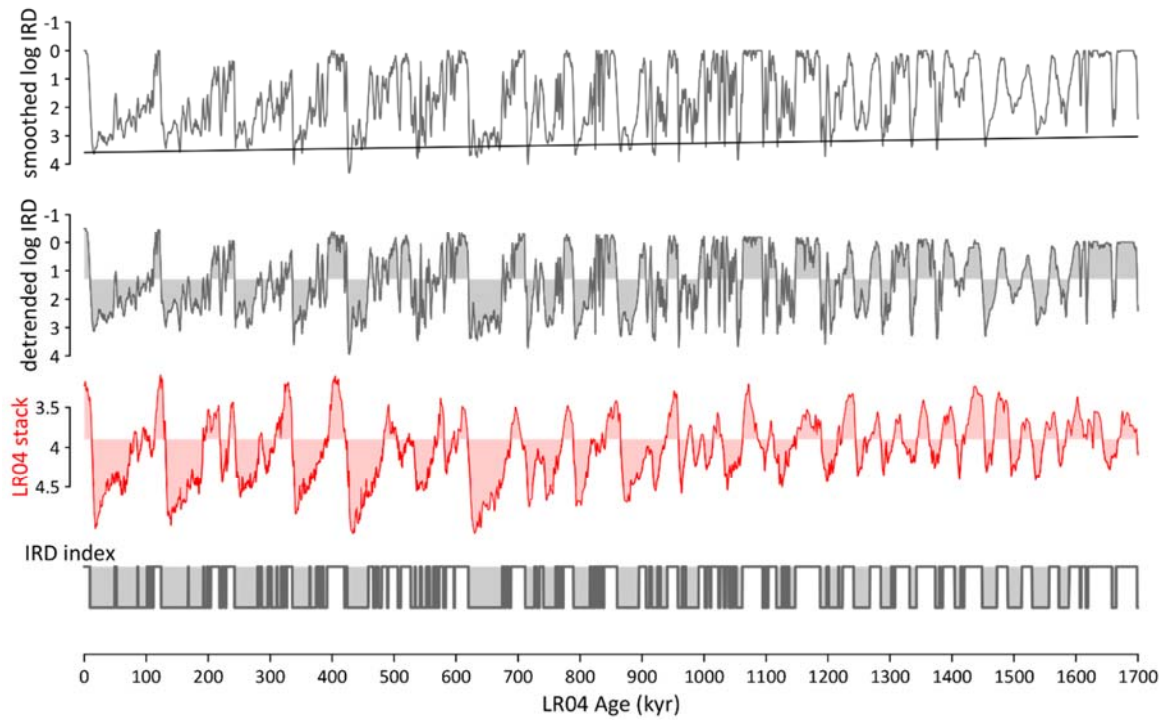
449



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451 **Fig. S8.**

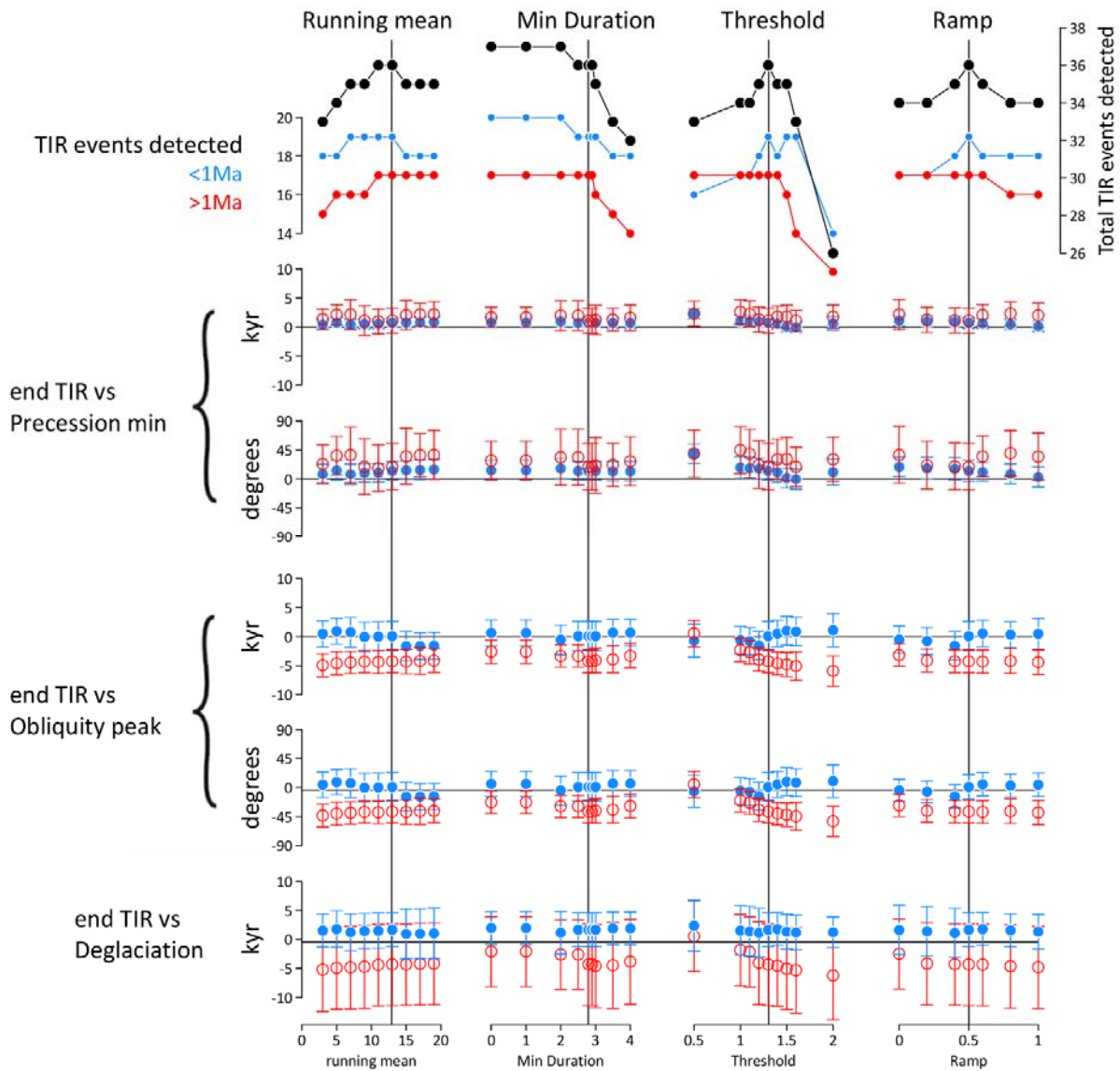
452 Algorithm for assessing the timing of IRD events relative to interglacials and deglacial
 453 transitions as well as minima and maxima in orbital parameters (not shown). From top to bottom:
 454 IRD accumulation from ODP Site 983 on linear and log scales, smoothed (13pm) and detrended
 455 log IRD with threshold for identifying low versus high (significant) IRD (1.3 on log scale
 456 equivalent to $20\text{grains}\cdot\text{cm}^{-2}\cdot\text{kyr}^{-1}$ on linear scale), IRD index with start (blue diamonds) and end
 457 (orange diamonds) of significant ice rafting according to the algorithm (see supplementary text),
 458 the LR04 stack with interglacials (red circles) and deglacials (white diamonds) identified from
 459 records of smoothed (10kyr) LR04 and smoothed (10kyr) dLR04/dt (bottom). Note that start of
 460 significant ice rafting following an interglacial typically occurs when LR04 has increased to
 461 $\sim 3.9\%$, which highlights the close relationship between ice rafting at Site 983 and the LR04
 462 stack as an indicator of global ice volume.



463

464 **Fig. S9.**

465 Full 1.7Myr IRD index used to identify start and end of significant ice rafting. Upper curve
466 shows 13-point smoothed log IRD and linear trend (0.5/1700kyr) subtracted to produce
467 detrended curve (below). Shaded fill for detrended curve delineates intervals of significant ice
468 rafting (log IRD > 1.3).
469



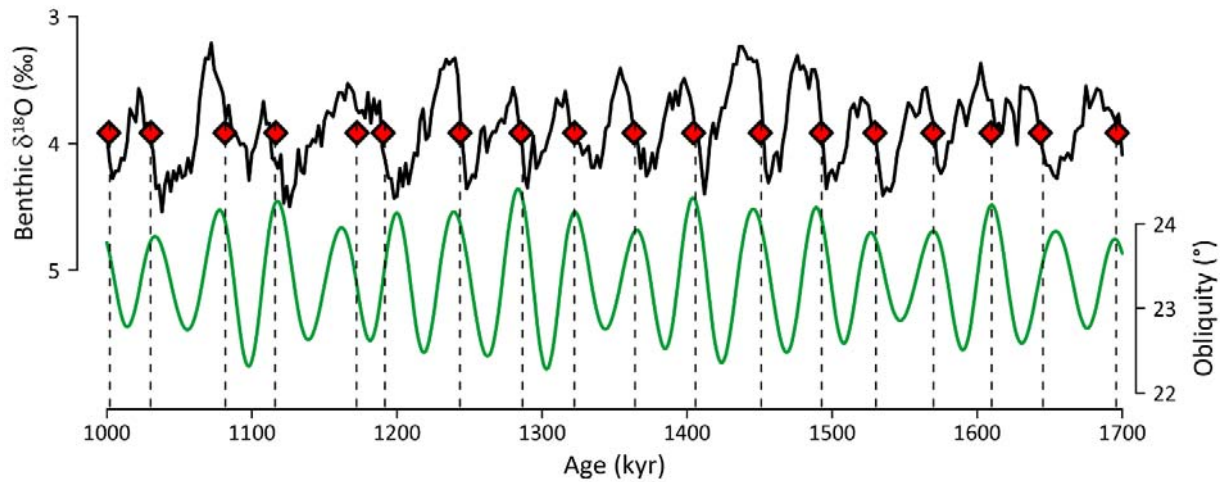
470

471 **Fig. S10.**

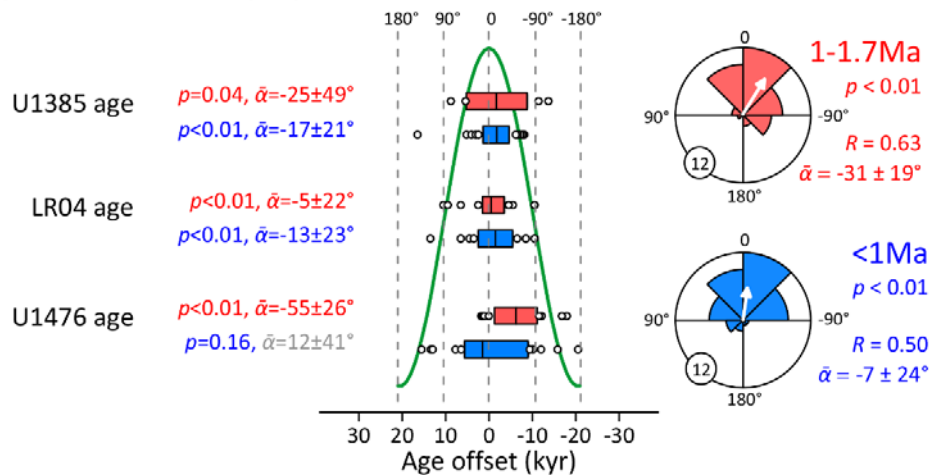
472 Sensitivity analysis for the various parameters used in the IRD algorithm (vertical lines represent
 473 implemented values). ‘Running mean’ is the smoothing applied to the logIRD record prior to
 474 construction of the IRD index and ‘Ramp’ represents detrending the record to account for
 475 generally higher levels during the Late Pleistocene. ‘Min Duration’ is the minimum duration of a
 476 TIR event and ‘Threshold’ is the level above which ice rafting is considered significant. The
 477 main conclusions concerning the relative timing of TIR events with respect to orbital peaks and
 478 deglaciation as a function of $\delta^{18}\text{O}$ are rather insensitive to the choice of parameter value except
 479 for very low values of ‘Threshold’ (see Methods). Error bars in lowermost row represent 1σ , all
 480 others represent 80% confidence interval (CI).

481

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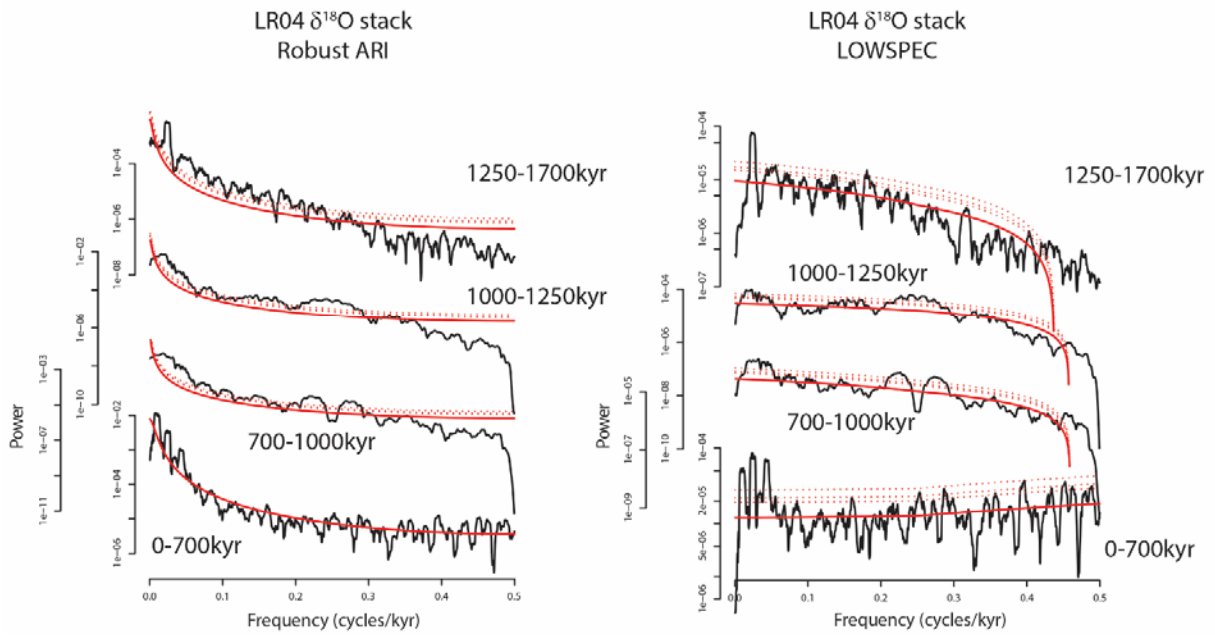
Deglaciation wrt obliquity maxima



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484

485 **Fig. S11.**

486 Deglacial transitions picked by our algorithm (red diamonds) align closely with rising to
 487 maximum obliquity. This is not surprising for the LR04 age model (which is tuned to obliquity
 488 and precession) but a similar relationship is observed for all three age models employed here.
 489 Box plots for each age model represent median and interquartile range, all other data-points are
 490 shown. Red and blue colors represent pre- and post-1Ma. Rose diagrams combine results from
 491 the 3 age models (see methods): Lower values of p suggest higher likelihood of a non-uniform
 492 distribution, R is mean resultant vector ($R \rightarrow 1$ as data converge), $\bar{\alpha}$ is mean direction with 95%
 493 confidence interval or 80% CI (grey text) for $p > 0.15$. Direction of white arrow = $\bar{\alpha}$, length =
 494 $R \cdot \text{radial axis}$. Circled number is length of radial axis.
 495

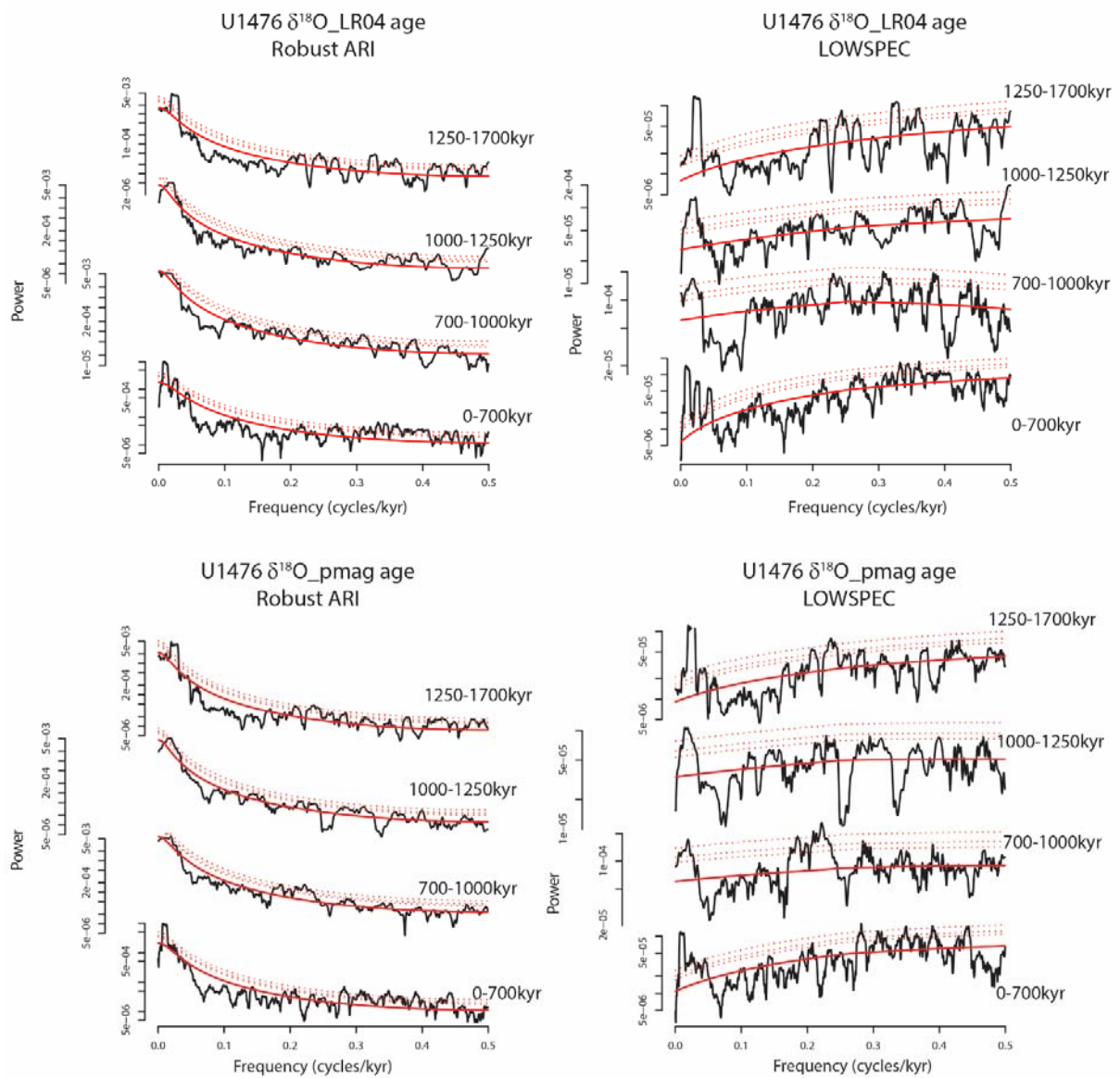


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498 **Fig. S12.**

499 Power spectra and red noise estimates out to the Nyquist frequency for the LR04 δ¹⁸O stack for 4
500 times intervals and 2 estimation methods.

501

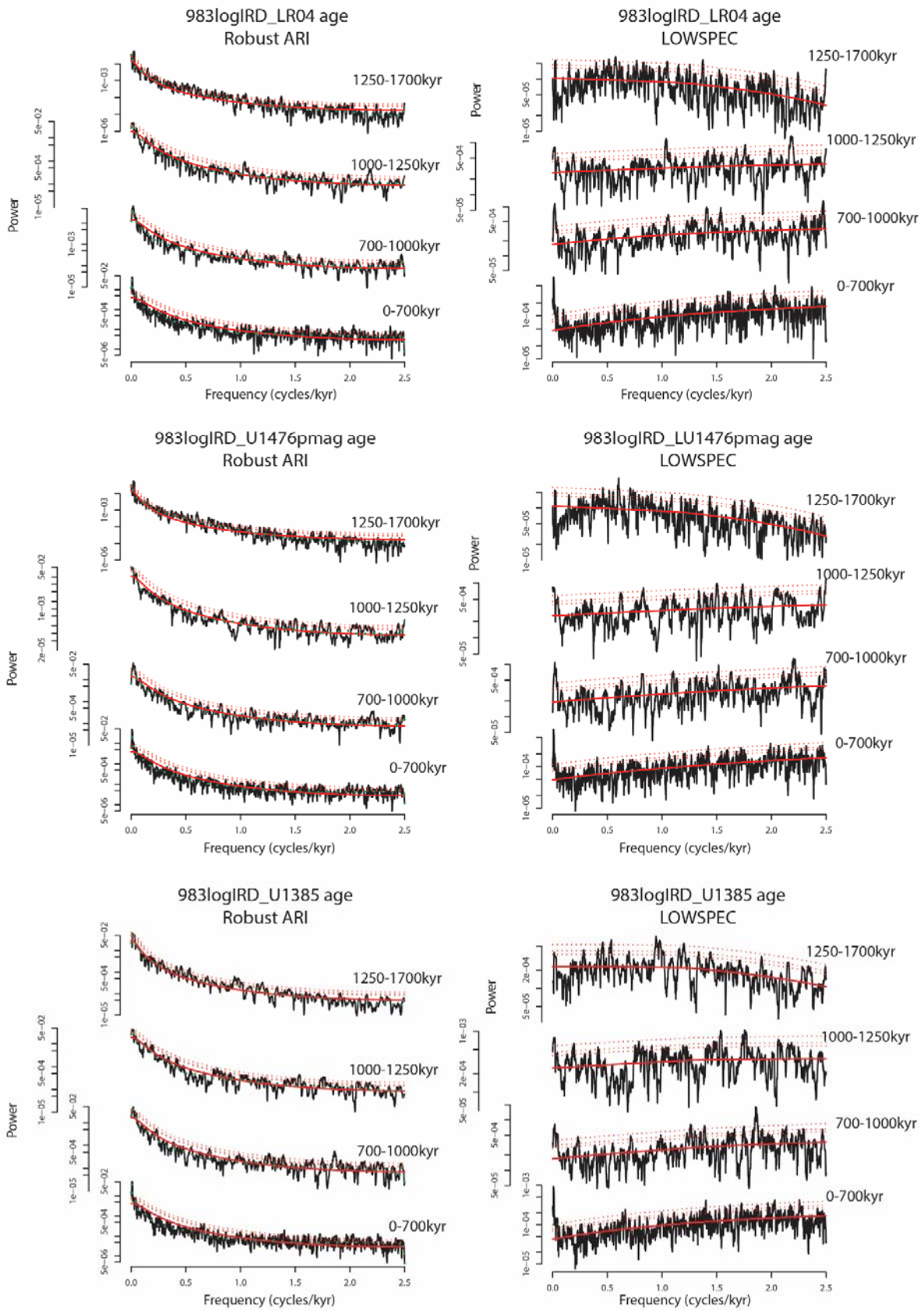


502
503

504 **Fig. S13.**

505 Power spectra and red noise estimates out to the Nyquist frequency for the U1476 $\delta^{18}\text{O}$ record
506 for 4 times intervals, 2 age models and 2 estimation methods.

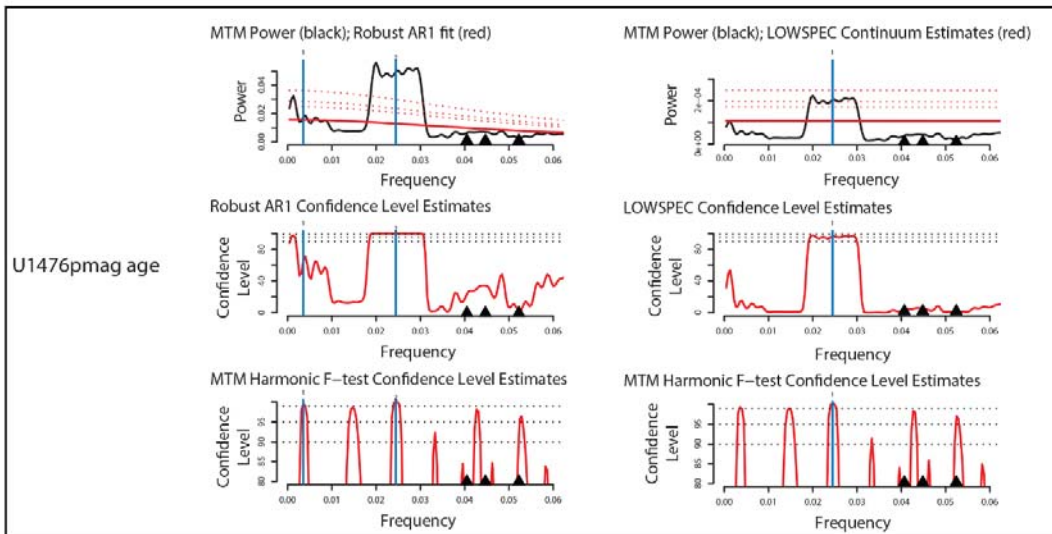
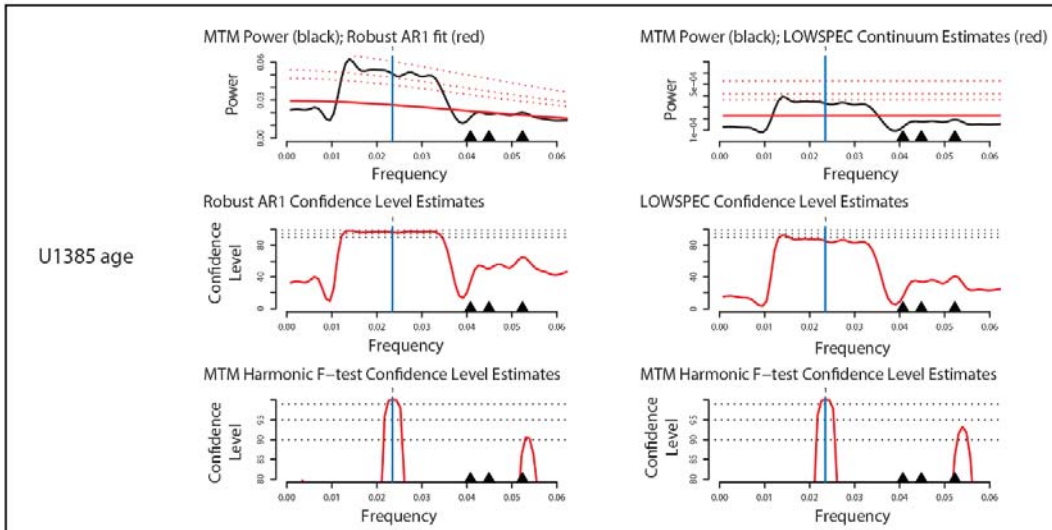
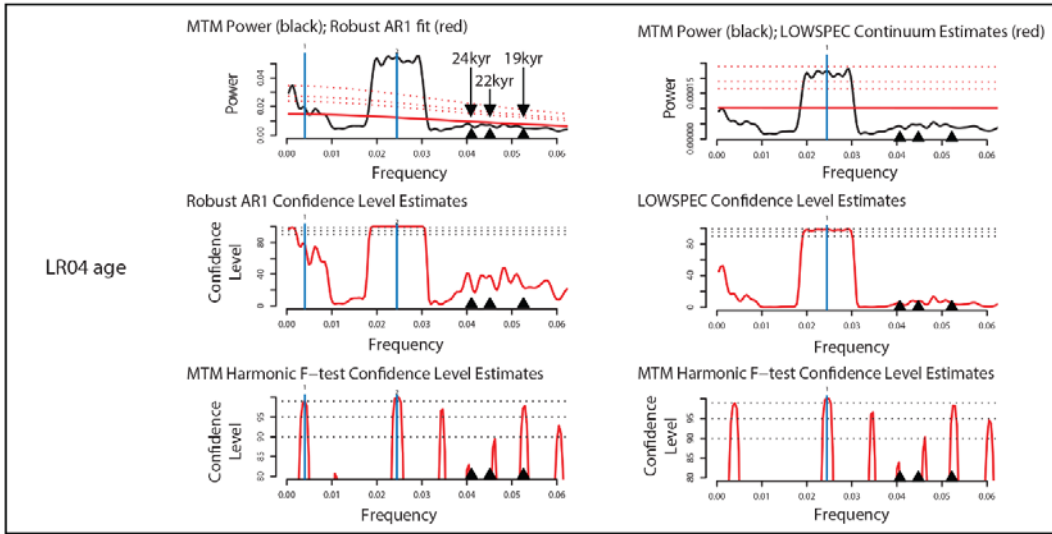
507



509 **Fig. S14 (previous page).**

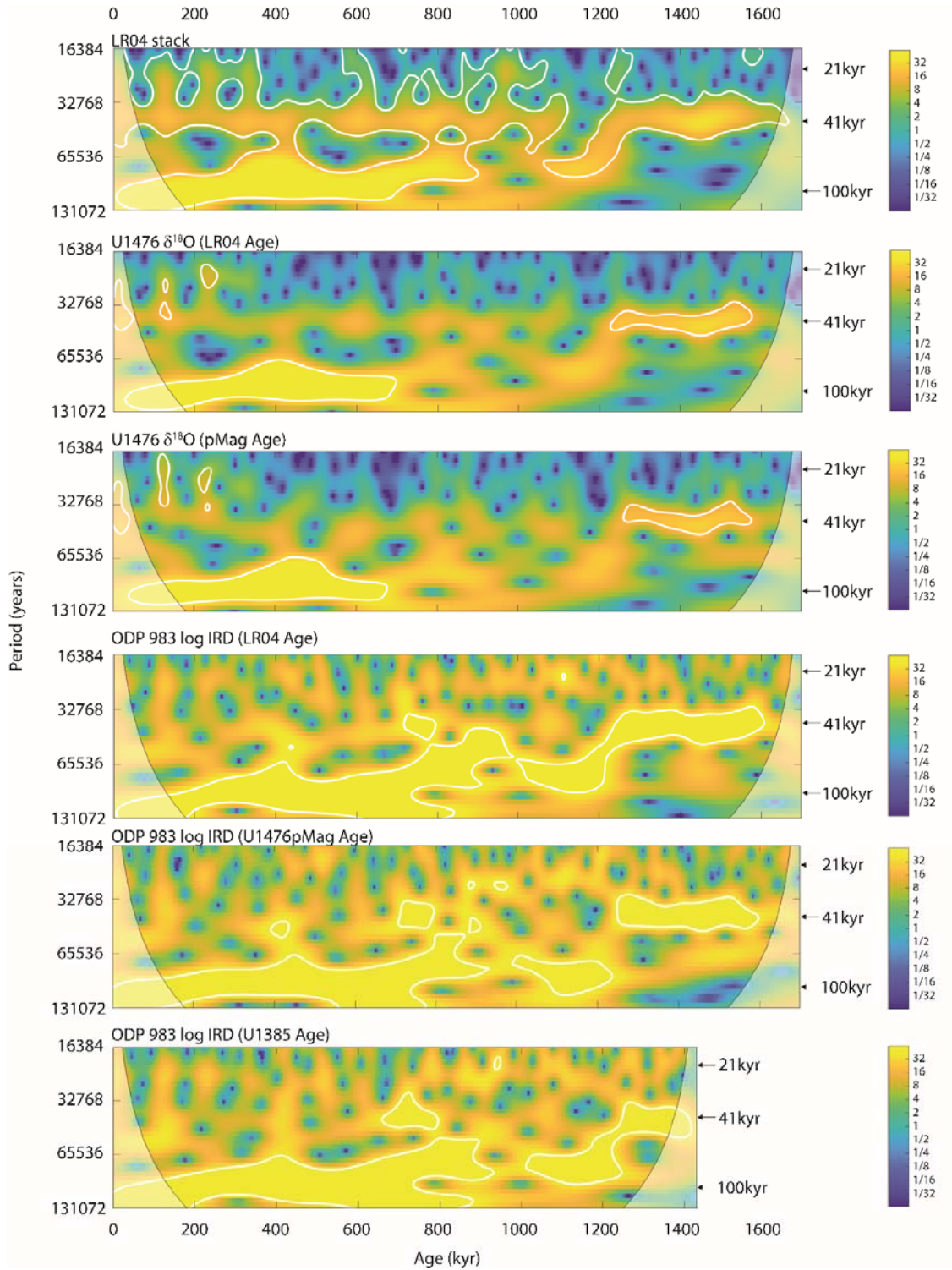
510 Power spectra and red noise estimates out to the Nyquist frequency for the logIRD record from
511 ODP Site 983 for 4 times intervals, 3 age models and 2 estimation methods.

512



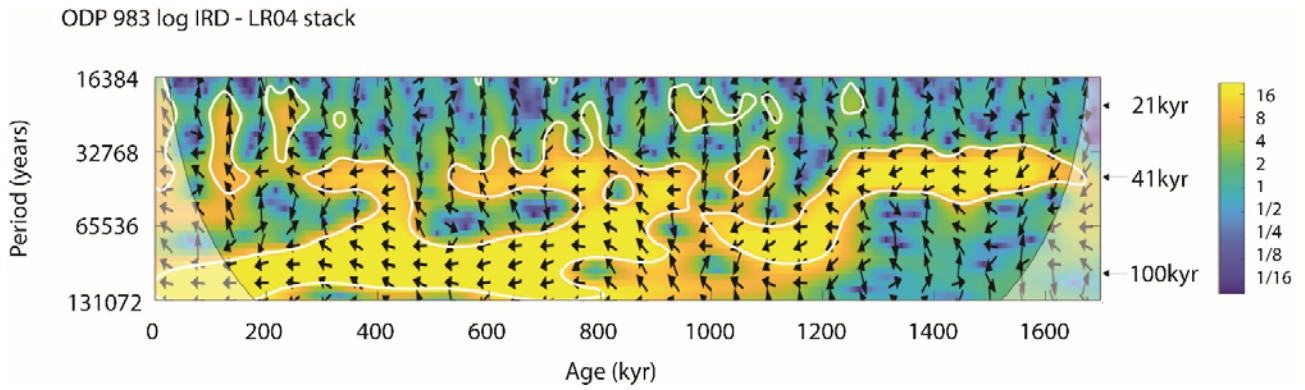
514 **Fig. S15 (previous page).**

515 Power spectra and red noise estimates out to 0.06 cycles/kyr for the logIRD record from ODP
516 Site 983 for the 1250-1700ka interval, using 3 age models and 3 estimation methods: AR(1),
517 LOWSPEC and a MTM harmonic F-test. Estimated significance within the precession band is
518 below the 90% threshold required to pass the AR(1) and LOWSPEC tests even though modest
519 power is observed with some peaks having relatively high confidence according to the harmonic
520 F-test (see Methods text).
521



522 **Fig. S16.**

523 Wavelet transforms (44) of LR04, U1476 benthic $\delta^{18}\text{O}$ and ODP 983 log IRD on their various
 524 timescales. Yellow colors indicate greater significance. The white contour designates the 5%
 525 significance level against red noise and the cone of influence is shown as a lighter shade.



526

527 **Fig. S17.**

528 Cross wavelet transform (44) of log IRD (on its LR04 age model) versus the LR04 benthic $\delta^{18}\text{O}$
 529 stack. Yellow colors indicate greater coherence. The 5% significance level against red noise is
 530 shown as a white contour. An in-phase relationship is signified by arrows pointing to the left.
 531 Note that the significance level may be overestimated as a result of strong power within either of
 532 the individual wavelets (as shown in Fig. S16) (45).
 533

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537 **Table S1.**538 ⁴⁰Ar/³⁹Ar dates (15) used to constrain absolute age models pMag and U1476pMag.

539

Event	Depth (ODP 983 Splice)	983 Depth uncertainty (2 sigma)	Depth (U1476 CCSF)	Depth uncertainty (3 sigma; max deviation)	U1476 Depth uncertainty (1 sigma) input for 'Undatable'	⁴⁰ Ar/ ³⁹ Ar Age	Age uncertainty (2 sigma)	Notes
	m	m	m	m	m	kyr	kyr	
Pringle Falls 2	24.49	0.05	4.63	0.01	0.03	212	13	
Bermuda	47.71	0.05	9.06	0.39	0.13	412	3	
La Palma	69.93	0.05	12.66	0.16	0.06	580	8	
Osaka Bay	79.73	0.27	14.58	0.38	0.19	677	22	
Matuyama-Brunhes	90.47	0.40	16.83	0.47	0.25	773	2	
MB precursor	93.11	0.10	17.36	0.04	0.05	795	2	
Kamikatsura	102.73	0.15	19.00	0.05	0.08	867	2	
Santa Rosa	109.27	0.13	20.26	0.06	0.07	927	2	
Top Jaramillo	117.76	0.10				990	4	Excluded from U1476 age model due to ambiguous $\delta^{18}\text{O}$ correlation
Base Jaramillo	131.76	0.28	22.92	0.71	0.27	1070	3	
Punaruu	138.83	0.10	23.56	0.14	0.07	1126	2	
Top Cobb Mt	147.92	0.15	24.80	0.20	0.10	1186	1	
Base Cobb Mt	151.31	0.13	25.38	0.23	0.10	1221	11	
Bjorn	157.65	0.20	26.27	0.07	0.10	1258	31	
Top Olduvai	247.03	0.20	39.73	0.17	0.11	1787	15	

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542 **Table S2.**

543 Phase relationships and significant (>90% confidence level) periods in the record of log(IRD)
 544 from ODP Site 983 versus orbital parameters and deglaciation as a function of benthic $\delta^{18}\text{O}$. Red
 545 and blue text highlights differences before and after 1Ma.
 546

Interval	Phasing						Significant periods (logIRD)		
	'Inception'		'Termination/Deglaciation'				19 - 24kyr	41kyr	80 - 100kyr
	Onset IRD vs obliquity	Onset IRD vs precession	End TIR vs obliquity	End TIR vs precession	End TIR vs deglaciation	Deglaciation vs obliquity			
1-1.7Ma	Decreasing obliquity Fig. 5	N/A Fig. 5	Increasing obliquity Fig. 5	Min precession Fig. 5	Leading or coincident Fig. 6c	Max obliquity Fig. S11	After 1.25Ma Fig. 3	✓ Fig. 3	After 1.25Ma Fig. 3
0-1Ma	Decreasing obliquity Fig. 5	N/A Fig. 5	Max obliquity Fig. 5	Min precession Fig. 5	Coincident Fig. 6c	Max obliquity Fig. S11	✓ Fig. 3	✓ Fig. 3	✓ Fig. 3

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