Persistent influence of obliquity on ice age terminations since the Middle Pleistocene transition

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Radiometric dating of glacial terminations over the past 640,000 years suggests pacing by Earth’s climatic precession, with each glacial-interglacial period spanning four or five cycles of ~20,000 years. However, the lack of firm age estimates for older Pleistocene terminations confounds attempts to test the persistence of precession forcing. We combine an Italian speleothem record anchored by a uranium-lead chronology with North Atlantic ocean data to show that the first two deglaciations of the so-called 100,000-year world are separated by two obliquity cycles, with each termination starting at the same high phase of obliquity, but at opposing phases of precession. An assessment of 11 radiometrically dated terminations spanning the past million years suggests that obliquity exerted a persistent influence on not only their initiation but also their duration.

A major challenge of testing the orbital (Milankovitch) theory of the ice ages is the uncertainty associated with the chronology of marine records. Orbital solutions are very accurate over the Pleistocene (7), but the age profile of deep-ocean sediments, where much of the evidence for global ice volume changes is preserved, often has large errors. Astronomical tuning of ocean records renders any test of the Milankovitch hypothesis invalid because of circular logic. Testing theories of orbital forcing ultimately requires ocean sediment records firmly anchored in absolute time.

A poorly understood feature of Pleistocene glacial-interglacial (G-IG) cycles is the change in the period of terminations—the relatively rapid switches from glacial to interglacial climate—during the Middle Pleistocene transition (MPT) 1.25 to 0.7 million years ago (Ma) (2–7). Evidence from ocean sediments shows that most terminations occurred every ~40,000 years (40 kyr) prior to the MPT but averaged ~100 kyr in the post-MPT interval (5). Although the precise mechanisms for this switch remain unclear (4–6), recent studies highlight the critical interval of marine isotope stages (MIS) 24–22, when major changes in ocean circulation and ice sheet dynamics occurred (7, 8). This interval includes a “failed termination” at the MIS 24–23 transition, the residual ice from which probably contributed to the steplike increase in global ice volume observed over the subsequent MIS 22 glacial (the “900-ka event”) (5, 9). Accordingly, the interval bounded by the MIS 26–25 and 22–21 transitions—terminations XII and X (TXII and TX), respectively—is often erroneously considered to be the first “100-kyr cycle” (7).

The transition to the “100-kyr world” occurred without considerable shifts in astronomical parameters (4, 7, 8), implying that internal forcing changed the way the Earth system responded to orbital variations. The ~40-kyr period for pre-MPT G-IG cycles (5, 10) suggests pacing by changes in Earth’s axial tilt, or obliquity (7), which affects the degree of seasonality in a given year. At high obliquity, the polar latitudes in both hemispheres receive more summer insolation, potentially inducing substantial ice sheet ablation (11). The dominance of a ~100-kyr periodicity for post-MPT terminations has been linked to forcing by changes in Earth’s eccentricity (1, 12), but each ~100-kyr interval is more likely a cluster of climatic precession (herein, precession) and/or obliquity (8, 13, 14) cycles whose sum averages to ~100 kyr when viewed over the long term. This is supported by an Asian monsoon speleothem record spanning all terminations over the past 640 kyr (15), which shows a spacing of four or five precession cycles. Precisely what happened, in terms of forcing, between the MPT and TVII (~635 thousand years ago (ka)) remains unclear; yet the answer may assist in our understanding of the MPT itself.

Studies focusing on G-IG cycles that traverse the MPT (7, 8, 13) have relied on stacked records of deep-ocean benthic oxygen isotope (δ18O) changes (5, 13), which are driven primarily by variations in global ice volume (10) but which also record a prominent deep-ocean temperature component (7). Given the inability to date marine sediments beyond the limits of radiocarbon dating, and given the phase uncertainties between the benthic ice volume–proxy record and astronomical (or other) tuning targets, precociously datable archives are required. We independently determined the age of terminations across the MPT by tying the radiometric chronology from a speleothem δ18O time series to North Atlantic ocean sediment records. We then compared our results with astronomical and insolation parameters (1, 9, 13, 16) for terminations since 640 ka (15, 17).

Our speleothem record comes from Corchia Cave (Alpi Apuane, Italy) (18–20) and spans the interval ~970 to ~810 ka, encompassing two complete terminations (TXII and TX) and one uncompleted termination (7, 8). A composite δ18O time series derived from four stalagmites (CC8, CC30, CC119, and CC122) and a subaqueous speleothem (CD3) (Fig. 1) was anchored in absolute time using the U-Pb method (18, 20–22) (figs. S1 and S2 and table S1). Almost the entire record is replicated, and concordance between both the individual stalagmite age models (fig. S3A) and the overlapping stable-isotope profiles (fig. S4A) allows all U-Pb ages to be placed onto a common depth scale to produce a composite age–depth model (18, 20) (fig. S3B). After accounting for all sources of random and correlated uncertainties (20), the average model–age precision over the whole record is <7 kyr (95% confidence interval) (fig. S3C)

The climate at Corchia Cave has strong teleconnections with circulation changes in the North Atlantic (19, 23), from where well-resolved marine records of glacial terminations have emerged (24, 25). Previous studies have shown that Corchia speleothem δ18O tracks changes in sea surface temperature (SST) recorded off the Iberian margin (19, 26) through the effect of SST on moisture advection to, and ultimately rainfall amount above, the cave site. However, during terminations, the link between regional SST and speleothem δ18O is overridden by large decreases in the δ2H of surface ocean water (δ2H0) caused by collapse of continental ice sheets (18). This flux of low δ2H0 values introduces a “source effect” that is captured in rainfall δ18O at the cave, then recorded in its speleothems (27).

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speleothems, the δ¹⁸O of planktic foraminifera from the Iberian margin and the western Mediterranean Sea is also sensitive to changes in both SST and δ¹⁸Osw. SST dominates the signal, except during times of large meltwater incursions, such as terminations (23, 24, 27–29), making the planktic δ¹⁸O a robust tuning target for synchronizing the cave and ocean records (18). Accordingly, we tied our speleothem chronology to a newly produced, high-resolution ocean sediment record from North Atlantic Integrated Ocean Drilling Program (IODP) site U1385 (30) by synchronizing the planktic δ¹⁸O to the Corchia δ¹⁸O time series (Fig. 1, figs. S4B to S6, and table S2) (18). Previous cores from this drilling site (23, 24) register the commencement of terminations as large decreases in benthic δ¹⁸O. The consistency of this pattern can be evaluated by comparing the phasing of these decreases with changes in planktic δ¹⁸O and the tetraunsaturated alkenone (C₃₇:₄) meltwater proxy from the same core (31), together with changes in SST at IODP site U1387, nearby in the Gulf of Cádiz (Fig. S5).

The multiproxy ocean data show that the commencement of large, near-monotonic benthic δ¹⁸O decreases for both terminations is approximately synchronous with rapid SST cooling and increased percent concentration of C₃₇:₄ (Fig. 2) caused by meltwater from ice sheet collapse reaching the Iberian margin. These terminal stadial events provide unequivocal evidence for the onset of the two terminations, as is the case with younger terminations recorded at the Iberian margin (23, 29). The larger percent C₃₇:₄ value witnessed during TX relative to TXII is consistent with the concurrent planktic δ¹⁸O decrease and SST cooling at the beginning of the termination, suggesting release of a larger meltwater volume (Fig. 2). This caused a prominent decoupling between SST and planktic δ¹⁸O, similar to that observed during TII (23, 27, 29). Applying the Corchia chronology to both ocean records allows the onset of TXII and TX to be dated with a precision of ~0.5%, with TXII starting at 960.1 ± 4.7 ka, and TX at 875.4 ± 4.7 ka (Fig. 2). The corresponding LR04 benthic stack (5) onset ages for TXII and TX suggest an intervening interval of 92 kyr (Fig. 1D). Our newly generated chronology yields a somewhat shorter interval of ~85 ± 7 kyr (Fig. 2), constituting the first radiometric evidence that the period between TXII and TX represents a single G-IG spanning about two obliquity and four precession cycles. The chronology also reveals that both terminations started at similar phases of high obliquity, whereas the corresponding precession phases were almost diametrically opposed (Fig. 2). Furthermore, the two terminations were completed at different rates (Fig. 1C). At TXII, ice sheet collapse was initiated when obliquity and precession approached maximum values.
resulting in strong Northern Hemisphere (NH) summer insolation and a very rapid termination, whereas the more prolonged TX started at near-minimum precession but was completed at near-maximum obliquity and precession (Fig. 2). These observations suggest that insolation changes more closely associated with obliquity than with precession initiated the two terminations, while summer insolation status at initiation controlled termination duration.

Next, we explore whether these relationships hold for TVII to TI, for which previous assessments favor precession over obliquity (15, 17). Estimates for their timing can be determined using a principle similar to our approach for TXII and TX. The precisely dated Chinese speleothems, to which the younger terminations are anchored, register perturbations to the Asian monsoon at the onset of a terminal stadial event (15, 17), enabling the start of each termination to be tied to a radiometric chronology (table S3 and fig. S7) (18). Our analysis of all 11 radiometrically constrained terminations shows that the phasing of precession and obliquity at the start of TXII and TX falls within the range of values for post-MPT terminations (Fig. 3A, right panel). However, there is a clear obliquity phase lead of at least ~30° (table S4) (18) for 8 of the 11 terminations (Fig. 3, B and C). Seven terminations began when integrated summer energy >275 W/m² at 65°N (predominantly obliquity-driven) (16) was above average (Fig. 3D), whereas NH summer insolation intensity at 65°N (predominantly precession-driven) was below average in eight cases (Fig. 3E). A similar finding emerges for the termination midpoints, the classical metric for quantifying termination pacing (5): These midpoints are, overall, positioned at closer proximity to maximum integrated summer energy values (Fig. 3D) than to maximum NH summer insolation intensity values (Fig. 3E). We also find that the interval between each termination midpoint is a multiple of both precession (23 ± 2 kyr) and obliquity (~41 ± 7 kyr) periods (table S4) (18). Finally, terminations never commence in a precession cycle that does not align with the rising limb or peak of an obliquity cycle (Fig. 3, B and C). In light of this evidence, a predominance of precession over obliquity seems unlikely in the pacing of post-MPT terminations (15, 17). Obliquity has clearly played an equal, if not greater, role in their timing.

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for each one to run to completion (18). We find that duration is significantly correlated with caloric summer half-year energy (approximately equal contributions from obliquity and precession), integrated summer energy, and NH summer insolation intensity (all at 65°N) (Fig. 3F) at the commencement of a termination; the correlation with the precession index is much weaker but remains significant for tilt. This reinforces the strong role of obliquity in post-MPT terminations.

The radiometrically constrained ensemble of 11 terminations allows us to evaluate the findings of a recent study implicating a combination of obliquity and precession in controlling termination timing over the past 1 million years (13). In this study, an approximate age of each termination midpoint was estimated using the rate of change in benthic δ18O (13), climatic precession (1), integrated summer energy (>275 W/m²) at 65°N (16), and July insolation intensity at 65°N (1) and caloric summer half-year energy at 65°N (9). The blue squares highlight the data for TX and TXII. Underlined r values are statistically significant (P < 0.05; degrees of freedom = 9).

The ~100-kyr G-IG spacing consists of clusters of two (80-kyr) or three (~120-kyr) tilt cycles (13, 14), with the interval between each termination controlled by obliquity, but the exact timing within a given cycle occurring when Earth is at perihelion during the NH summer solstice (i.e., maximum precession) (13). Our results show that the spacing of termination midpoints is consistent with obliquity forcing (Figs. 3B and 4A), and that the midpoints are most consistently aligned...
Fig. 4. Comparison of the timing of 11 termination midpoints and normalized orbital and insolation metrics. (A) Termination timing (red vertical dashed lines) versus obliquity (light and dark blue shading) and climatic precession (dark gray curve) (1). Precession is multiplied by −1, as in Fig. 2. Gray vertical bands are the 95% uncertainties of the midpoint-age estimates, which for the younger terminations (1B) are small compared with the line thickness. (B) Termination timing, as in (A), versus an insolation forcing metric that combines both obliquity and climatic precession variability (13, 1B).

with peaks in an insolation forcing metric (almost identical to caloric summer half-year insolation at 65°N), which integrates approximately equal amounts of obliquity and precession (Fig. 4, A to C) (13, 1B).

Newly determined radiometric ages for TXII and TX coupled with a reassessment of well-dated younger terminations (TVII to TVI) suggest that obliquity pacing of G-H cycles continued beyond the 40-kyr world. A termination onset was more likely to occur at a higher phase of obliquity than precession. Once ice sheet collapse was initiated, insolation changes driven by both precession and obliquity propelled the climate toward full interglacial conditions, but at a rate dependent upon the prevailing levels of predominantly obliquity-controlled summer energy. The results presented here suggest that the term “100-kyr world” is both inaccurate and misleading, and that its usage should probably be discontinued.

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Data and materials availability: All data produced and used in this study are available from the World Data Center PANGAEA online repository at www.pangaea.de. The computer code for the finite growth rate-depth-age model is available upon request from J.C.H. (j.hellstrom@unimelb.edu.au) and will be published in full in a future publication.

SUPPLEMENTARY MATERIALS
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Materials and Methods Figs. S1 to S4 Tables S1 to S4 References (32–67)
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Persistent influence of obliquity on ice age terminations since the Middle Pleistocene transition

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An underground record of past deglaciations
Understanding more exactly how the timing of deglaciations depends on changes in insolation, or the energy received by Earth from the Sun, requires precise and independent records of both environmental change and solar energy input. Bajo et al. strengthened the weak link of that two-member chain, the environmental record, by developing a precise, radiometrically dated chronology of the 11 deglaciations of the past million years derived from speleothems. This allowed them to show more clearly how the initiation and duration of glacial terminations over that period depended on solar obliquity and precession.

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