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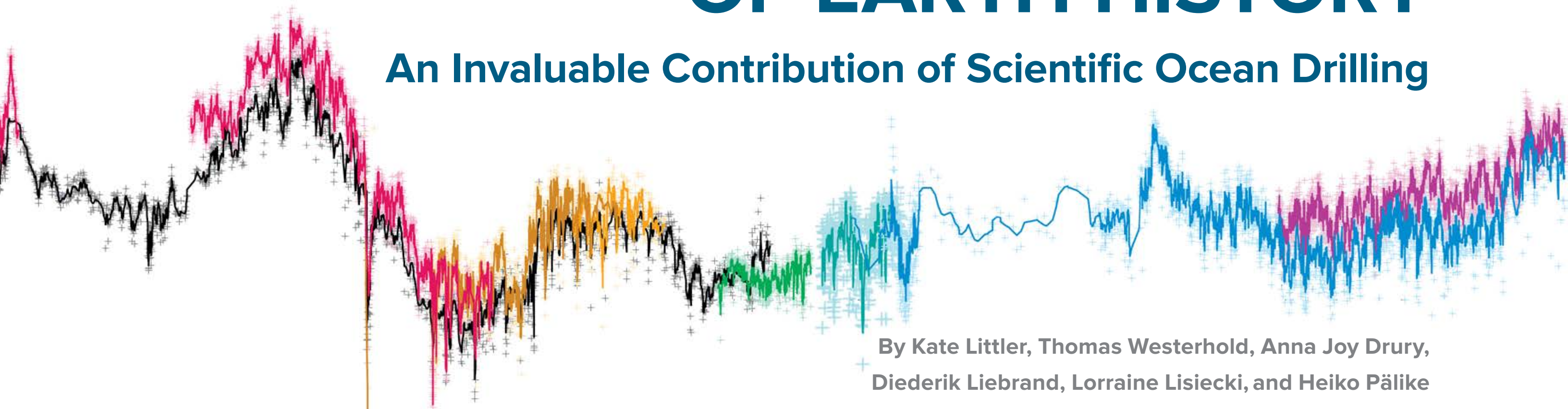
ASTRONOMICAL TIME KEEPING OF EARTH HISTORY

An Invaluable Contribution of Scientific Ocean Drilling



By Kate Littler, Thomas Westerhold, Anna Joy Drury, Diederik Liebrand, Lorraine Lisiecki, and Heiko Pälike

ABSTRACT. The mathematically predictable cyclic movements of Earth with respect to the sun provides the basis for constructing highly accurate and precise age models for Earth's past. Construction of these astronomically calibrated timescales is pivotal to placing major transitions and events in the geological record in their temporal context. Understanding the precise nature and timing of past events is of great societal relevance as we seek to apply these insights to constrain near-future climate scenarios. Scientific ocean drilling has been critical in this endeavor, as the recovery and analysis of high-quality and continuous marine sedimentary archives underpin such high-resolution age models for paleoclimate records. This article identifies key astronomically calibrated records through the past 66 million years (the Cenozoic) collected during multiple Deep Sea Drilling Project, Ocean Drilling Program, Integrated Ocean Drilling Program, and International Ocean Discovery Program expeditions, highlights major achievements, and suggests where future work is needed.

INTRODUCTION

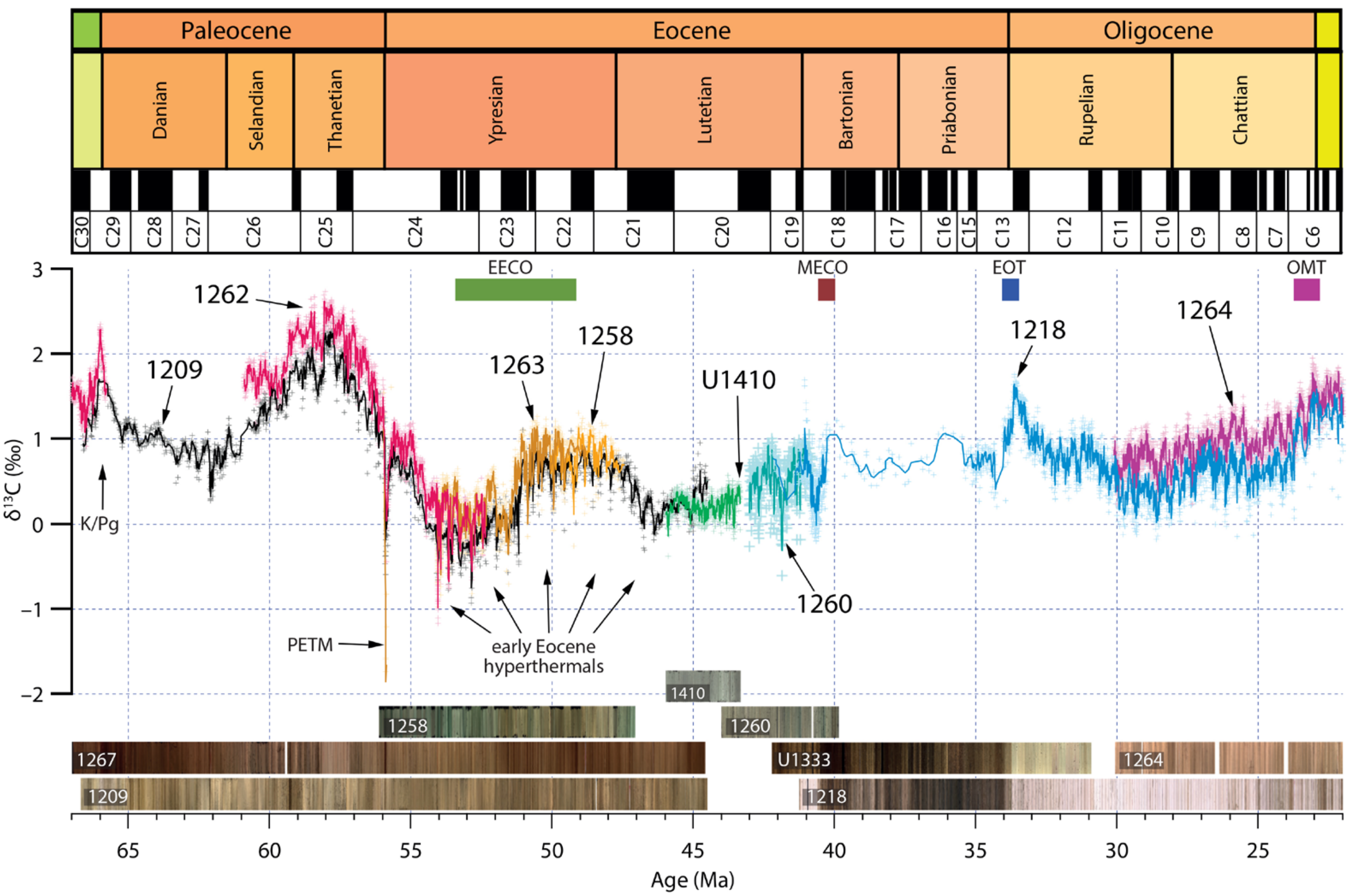
Five decades of scientific ocean drilling by the International Ocean Discovery Program (IODP) and its predecessors continue to provide unique sample material essential for developing highly accurate astronomically calibrated timescales. It has long been recognized that cyclic changes in both the absolute distance of Earth from the sun throughout the year and the angle of Earth's rotational axis influence the latitudinal distribution of incoming solar radiation (insolation) and, hence, the amplitude of the seasons (Milankovitch, 1941; Laskar et al., 2004). Through many processes within the Earth system, these quasi-cyclic changes in insolation pace global climate change (e.g., Hays et al., 1976). Time-series analysis of the high-resolution sediment archives provided by scientific ocean drilling clearly document the persistent response of the Earth system to astronomical climate forcing over the last 66 million years. In particular, records of elemental abundances in sediment derived from X-ray fluorescence (XRF) core scanning and of the stable isotope ratios of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) of bulk sediment and benthic foraminifera—which are proxies for water chemistry and combined temperature and ice volume—are dominated by variations corresponding to Earth's astronomical cycles of eccentricity (~400 kyr and ~100 kyr), obliquity (~41 kyr), and orbital precession (~23 kyr). The orbital imprint in deep ocean sediments is ubiquitous, providing an important means of time keeping as well as allowing investigation of internal Earth system feedback processes.

Here, we highlight the great contribution that scientific ocean drilling has made to constructing precise astrochronological timescales for the Paleogene (from 66 to 23 million years ago) and the Miocene to Pleistocene (from 23 million to 11,700 years ago).

THE PALEOCENE, EOCENE, AND OLIGOCENE

Paleoclimate records from the Paleogene greenhouse world provide a unique opportunity to constrain Earth's climate system behavior under similar atmospheric CO_2 concentrations projected for the year 2100, and to investigate in detail the causal relationships between astronomical forcing and climatic/cryospheric and carbon cycle responses. Within the Paleogene, the Paleocene and Eocene Epochs (~66–34 million years ago) were generally characterized by warm "greenhouse" climates, reaching peak temperatures during the Early Eocene Climatic Optimum (EECO; Zachos et al., 2008; Lauretano et al., 2018) and punctuated by orbitally paced "hyperthermals" (i.e., strong, short-lived heating events) such as the Eocene Thermal Maximum 2 (~54 million years ago; e.g., Stap et al., 2010; Figure 1). The spatial coverage and temporal resolution of records was very limited prior to recovery of high-quality, multiple-hole sedimentary successions from the Atlantic, including Ocean Drilling Program (ODP) Leg 207 (e.g., Sexton et al., 2011), ODP Leg 208 (e.g., Zachos et al., 2010; Littler et al., 2014; Lauretano et al., 2016, Westerhold et al., 2017), and IODP Expedition 342 (e.g., Boulila et al., 2018; Vahlenkamp et al., 2018). Important records were also recovered from the Pacific, including ODP Leg 198 (e.g., Westerhold et al., 2011, 2018), and IODP Expedition 320/321 (e.g., Westerhold et al., 2014). Both XRF and stable isotope records from these continuous archives provided spectacular new insights into climate dynamics of a warm world (Figure 1). In particular, eccentricity-modulated precession cycles are ubiquitous at these sites (e.g., Zachos et al., 2010; Littler et al., 2014; Lauretano et al., 2016; Westerhold et al., 2017).

Following long-term mid-late Eocene global cooling, as indicated by a gradual increase in $\delta^{13}C$ values, the largest shift in the climate state of the Cenozoic occurred during the Eocene-Oligocene climatic transition (EOT; ~34 million years ago; Figure 1), which marked the establishment of a larger and more permanent Antarctic ice cover that reached its continental margin (Coxall et al., 2005; Pälike et al., 2006b). The mid-Oligocene glacial interval (28–26 million years ago; Pälike et al., 2006b; Liebrand et al., 2017) was another major cooling episode characterized by a large but dynamic Antarctic ice sheet that varied in size on astronomical timescales. This was followed by warming and retreat of the Antarctic



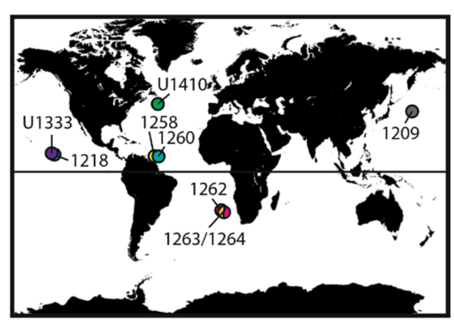


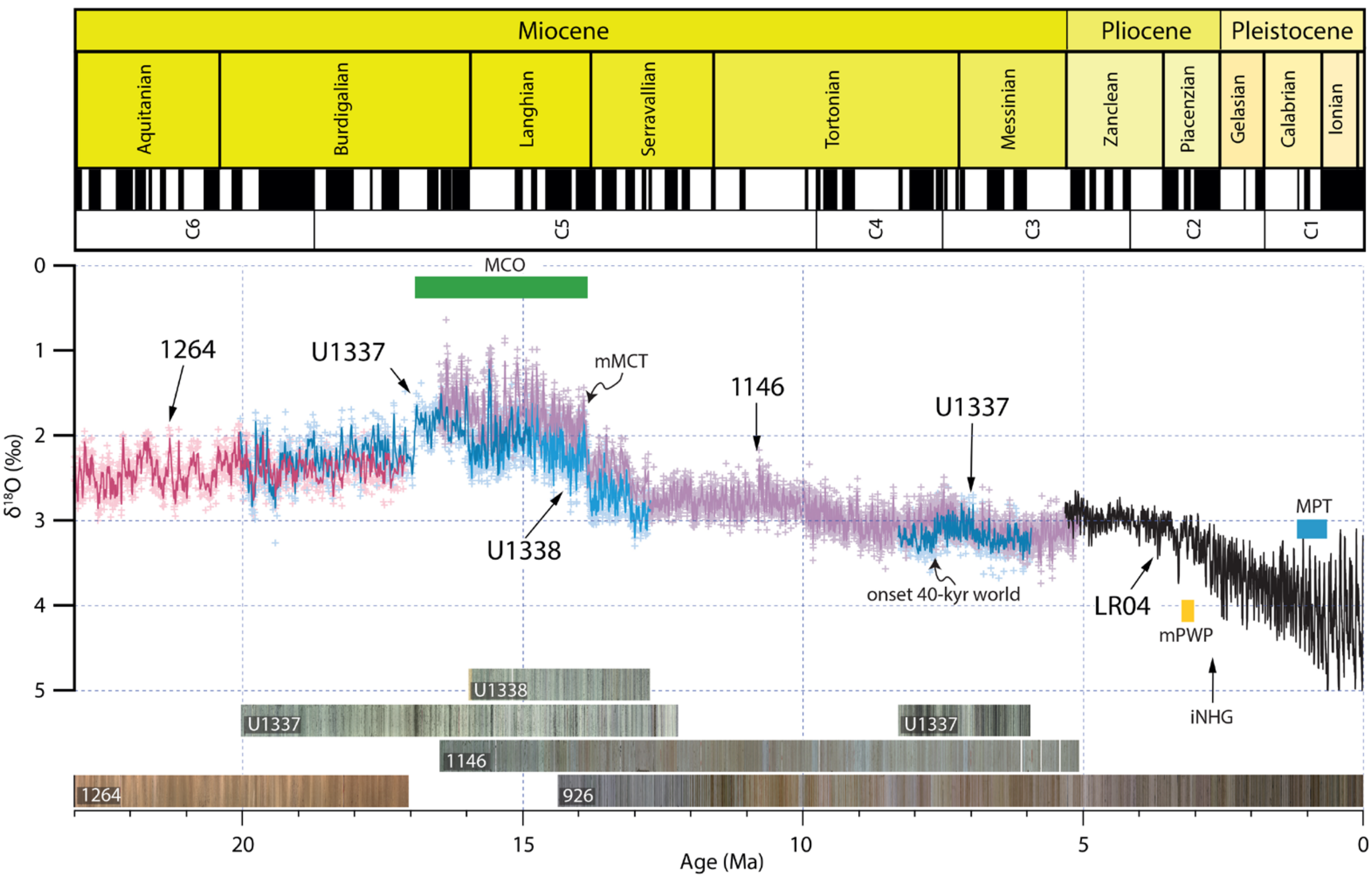
FIGURE 1. Compilation of the benthic carbon isotope data sets used in the construction of astronomically tuned age models in the Paleogene, plotted against age in millions of years (Ma). Data sources: ODP Site 1209 (Leg 198; Westerhold et al., 2011, 2018), ODP Site 1218 (Leg 199; Coxall et al., 2005; Pälike et al., 2006b; Coxall and Wilson, 2011), ODP Site 1258 (Leg 207; Sexton et al., 2011), ODP Site 1262 (Leg 208; Littler et al., 2014), ODP Site 1263 (Leg 208; Stap et al., 2010; Lauretano et al., 2015, 2016), ODP Site 1264 (Leg 208; Liebrand et al., 2016), IODP Site U1410 (Expedition 342, Vahlenkamp et al., 2018), and IODP Site U1333 (Expedition 320/321; Westerhold et al., 2014), all updated on the Westerhold et al. (2017) age model where appropriate. Variability in $\delta^{13}C$ best illustrates astronomical-scale variability in the warm, ice-free early Paleogene world. Colored lines represent three-point running means of the data. The inset map locates ODP and IODP sites for which data are presented. Representative core images from which these isotope data are generated are shown below the plot, with additional images from IODP Site U1333 spanning the middle-late Eocene, for which no published high-resolution isotope data (yet) exists. PETM = Paleocene-Eocene Thermal Maximum. MECO = Middle Eocene Climatic Optimum.

ice sheet, preceding the transient cooling and "re-glaciation" of Antarctica across the Oligocene-Miocene climatic transition (OMT; 23 million years ago; Billups et al., 2004; Pälike et al., 2006b; Liebrand et al., 2016; Beddow et al., 2018).

The Oligocene (~34–23 million years ago) was first astronomically calibrated using sediments recovered from the equatorial Atlantic (ODP Leg 154; Shackleton et al., 1999; Zachos et al., 2001) and Pacific (ODP Leg 199, Pälike et al., 2006b). This tuning has been confirmed at the ~400 kyr eccentricity level using sedimentary records from the Atlantic Ocean, including ODP Leg 177 (Billups et al., 2004), ODP Leg 154 (Pälike et al., 2006a), ODP Leg 208 (Liebrand et al., 2016), and IODP Expedition 342 (Van Peer et al., 2017). A more recent eccentricity-tuned record from the equatorial Pacific (IODP Expedition 320/321; Beddow et al., 2018) confirmed the accuracy of the numerical ages across the Oligocene–Miocene transition to the ~100 kyr eccentricity level.

THE MIOCENE, PLIOCENE, AND PLEISTOCENE

The Miocene (~23.0–5.3 million years ago) was characterized by a series of stepwise changes in global climate: warming culminating in the Miocene Climatic Optimum (MCO; 17.0–13.9 million years ago; Holbourn et al., 2014, 2015) as indicated by the lowest $\delta^{18}O$ values, cooling across the middle Miocene Climate Transition (mMCT; ~13.9 million years ago; Tian et al., 2013; Holbourn et al., 2014) portrayed by increasing $\delta^{18}O$ values, and the late Miocene onset of the "40-kyr world" (~7.7 million years ago; Drury et al., 2017, 2018b; Figure 2). The first Miocene deep-sea astronomically resolved records were recovered from ODP Leg 154 (Shackleton and Crowhurst, 1997; Shackleton et al., 1999; Zeeden et al., 2013; Wilkens et al., 2017) and ODP Leg 162 (Hodell et al., 2001)



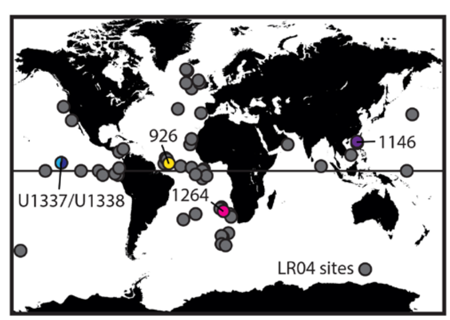


FIGURE 2. Compilation of selected benthic oxygen-isotope data sets used in the construction of astronomically tuned age models in the Miocene-Pleistocene, plotted against age in millions of years (Ma). Date sources: LR04 Stack (Lisiecki and Raymo, 2005), ODP Site 926 (Leg 154; Wilkens et al., 2017), ODP Site 1146 (Leg 184; Holbourn et al., 2007), ODP Site 1264 (Leg 208; Liebrand et al., 2016), IODP Site U1337 (Expedition 320/321; Holbourn et al. 2015; Drury et al., 2017), and IODP Site U1338 (Expedition 320/321; Holbourn et al., 2014). Benthic $\delta^{18}O$ records reflect both temperature and ice-volume variability and best represent astronomical-scale variability in the Neogene Icehouse. Colored lines represent three-point running means of the data. The inset map indicates ODP and IODP sites for which data are presented. Representative core images from which these isotope data are generated are shown below the plot, with an image from ODP Site 926, for which XRF elemental data exist but are not plotted. Note that all $\delta^{18}O$ data is offset by +0.64‰ relative to raw values, except for LR04 data, which are already corrected to equilibrium.

in the Atlantic, and ODP Legs 184 and 202 in the Pacific (e.g., Holbourn et al., 2005). Scientific ocean drilling has now provided continuous astronomical-scale stable isotope stratigraphies from 23 to 5 million years ago at key sites from ODP Legs 154, 162, 177, 184, and 208, and IODP Expedition 320/321 (Billups et al., 2004; Tian et al., 2013; Holbourn et al., 2014, 2015, 2018; Liebrand et al., 2016; Drury et al., 2017, 2018a,b). These records are underpinned by astrochronologies that are precise at the obliquity to precession levels, within the limitations of the numerical astronomical solutions. However, astronomically tuned records that combine isotope- and magnetostratigraphies are only available for the intervals spanning 24–16 million years ago (ODP Leg 177, Site 1090; Billups et al., 2004) and 8–6 million years ago (IODP Expedition 321, Site U1337; Drury et al., 2017).

The Pliocene and Pleistocene (5.3 million to 11,700 years ago) are characterized by a long-term global cooling onward from the mid-Pliocene Warm Period (mPWP, ~3 million years ago) and the intensification of Northern Hemisphere glaciation (iNHG; ~2.7 million years ago; Woodard et al., 2014). Superimposed on these long-term trends are astronomically paced oscillations between glacial and interglacial periods, which are observed in many high-resolution benthic $\delta^{18}O$ records and other climate-sensitive proxies. Overall, astronomical-band variance in benthic $\delta^{18}O$ increases exponentially during the long-term cooling trend and ice sheet expansion of the last 5 million years (Lisiecki and Raymo, 2007). Again, scientific ocean drilling has recovered astronomically resolved climate records from dozens of cores, providing the opportunity to create an average or stack of the synchronized global $\delta^{18}O$ signal ("LR04"; Lisiecki and Raymo, 2005). Stacks improve confidence in astronomically tuned age models by increasing the signal-to-noise ratio of astronomical responses (Imbrie et al., 1984), minimizing the impact of hiatuses or disturbances in individual cores, and providing an estimate of globally averaged sedimentation rates to assist with the tuning process. Within the Pleistocene, orbital tuning is associated with age uncertainties of 4 kyr (Lisiecki and Raymo, 2005). Robust astrochronologies made possible through stacked deep-sea drilling records are critical to identifying and understanding the major Plio-Pleistocene climate events, such as the mPWP (e.g., Dowsett et al., 2012) and the Mid-Pleistocene transition (MPT; ~1.2–0.6 million years ago) when the dominant mode of climate variability shifted from 41 kyr to 100 kyr cycles (e.g., Clark et al., 2006).

OUTLOOK

Despite much recent progress toward constructing a highly accurate Cenozoic stratigraphic framework using data from scientific ocean drilling cores, outstanding issues remain for several time periods. For example, there is a mid–late Eocene (~34–44 million years ago) "gap" in coverage, where until recently we lacked suitable cores to construct high-resolution geochemical proxy records (Figure 1). Continuing work on the IODP Expedition 320/321 sites, notably Site U1333 and sediments recovered from IODP Expedition 369 in 2017 in the Southeast Pacific, will hopefully close this stratigraphic gap. Multiple records spanning the same time interval will allow inter-basin and latitudinal differences in the expression of astronomically paced climate cycles to be fully explored, and will give greater confidence in the orbitally tuned age models for those intervals. A major outstanding goal is to acquire multiple astronomically tuned records from different ocean basins with which to generate a complete Cenozoic stack to match that already available for the Plio-Pleistocene. Despite the invaluable archive currently provided by ODP and IODP coring, the scarcity of suitable sediments, particularly from the high latitudes and the Indian Ocean, remains a critical challenge. Recent Indo-Pacific IODP expeditions (353–356, 363, 369, 371) and future Southern Ocean and Atlantic Ocean drilling can help resolve these issues. Ultimately, further scientific ocean drilling is essential to developing precise and accurate age models for Cenozoic climate reconstructions.

REFERENCES

Beddow, H.M., D. Liebrand, D.S. Wilson, F.J. Hilgen, A. Sluijs, B.S. Wade, and L.J. Lourens. 2018. Astronomical tunings of the Oligocene-Miocene transition from Pacific Ocean Site U1334 and implications for the carbon cycle. *Climate of the Past* 14:255–270, https://doi.org/10.5194/cp-14-255-2018.

Billups, K., H. Pälike, J.E.T. Channell, J.C. Zachos, and N.J. Shackleton. 2004. Astronomic calibration of the late Oligocene through early Miocene geomagnetic polarity time scale. *Earth and Planetary Science Letters* 224:33–44, https://doi.org/10.1016/j.epsl.2004.05.004.

Boulila, S., M. Vahlenkamp, D. De Vleeschouwer, J. Laskar, Y. Yamamoto, H. Pälike, S. Kirtland Turner, P.F. Sexton, T. Westerhold, and U. Röhl. 2018. Towards a robust and consistent middle Eocene astronomical timescale. *Earth and Planetary Science Letters* 486:94–107, https://doi.org/10.1016/j.epsl.2018.01.003.

Clark, P.U., D. Archer, D. Pollard, J.D. Blum, J.A. Rial, V. Brovkin, A.C. Mix, N.G. Pisias, and M. Roy. 2006. The middle Pleistocene transition: Characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2. *Quaternary Science Reviews* 25:3,150–3,184, https://doi.org/10.1016/j.quascirev.2006.07.008.

Coxall, H.K., P.A. Wilson, H. Pälike, C.H. Lear, and J. Backman. 2005. Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean. *Nature* 433:53–57, https://doi.org/10.1038/nature03135.

Coxall, H.K., and P.A. Wilson. 2011. Early Oligocene glaciation and productivity in the eastern equatorial Pacific: Insights into global carbon cycling. *Paleoceanography* 26(2), https://doi.org/10.1029/2010PA002021.

Dowsett, H.J., M.M. Robinson, A.M. Haywood, D.J. Hill, A.M. Dolan, D.K. Stoll, W.-L. Chan, A. Abe-Ouchi, M.A. Chandler, N.A. Rosenbloom, and others. 2012. Assessing confidence in Pliocene sea surface temperatures to evaluate predictive models. *Nature Climate Change* 2:365–371, https://doi.org/10.1038/nclimate1455.

Drury, A.J., T. Westerhold, T. Frederichs, J. Tian, R.H. Wilkens, J.E.T. Channell, H.F. Evans, C.M. John, M.W. Lyle, and U. Röhl. 2017. Late Miocene climate and time scale reconciliation: Accurate orbital calibration from a deep-sea perspective. *Earth and Planetary Science Letters* 475:254–266, https://doi.org/10.1016/j.epsl.2017.07.038.

Drury, A.J. G.P. Lee, W.R. Gray, M.W. Lyle, T. Westerhold, A.E. Shevenell, and C.M. John. 2018a. Deciphering the state of the late Miocene to early Pliocene equatorial Pacific. *Paleoceanography and Paleoclimatology* 33:246–243, https://doi.org/10.1002/2017PA003245.

Drury, A.J., T. Westerhold, D. Hodell, and U. Röhl. 2018b. Reinforcing the North Atlantic backbone: Revision and extension of the composite splice at ODP Site 982. *Climates of the Past* 14:321–338, https://doi.org/10.5194/cp-14-321-2018.

Hays, J.D., J. Imbrie, N.J. Shackleton. 1976. Variations in the Earth's orbit: Pacemaker of the ice ages. *Science* 194(4270):1,121–1,132, https://doi.org/10.1126/science.194.4270.1121.

Hodell, D.A., J.H. Curtis, F.J. Sierro, and M.E. Raymo. 2001. Correlation of late Miocene to early Pliocene sequences between the Mediterranean and North Atlantic. *Paleoceanography* 16:164–178, https://doi.org/10.1029/1999PA000487.

Holbourn, A., W. Kuhnt, M. Schulz, and H. Erlenkeuser. 2005. Impacts of orbital forcing and atmospheric carbon dioxide on Miocene ice-sheet expansion. *Nature* 438:483–487, https://doi.org/10.1038/nature04123.

Holbourn, A., W. Kuhnt, M. Schulz, J.-A. Flores, and N. Andersen. 2007. Orbitally-paced climate evolution during the middle Miocene “Monterey” carbon-isotope excursion. *Earth and Planetary Science Letters* 261(3–4):534–550, https://doi.org/10.1016/j.epsl.2007.07.026.

Holbourn, A., W. Kuhnt, M. Lyle, L. Schneider, O. Romero, and N. Andersen. 2014. Middle Miocene climate cooling linked to intensification of eastern equatorial Pacific upwelling. *Geology* 42:19–22, https://doi.org/10.1130/G34890.1.

Holbourn, A., W. Kuhnt, K.G.D. Kochhann, N. Andersen, and K.J. Sebastian Meier. 2015. Global perturbation of the carbon cycle at the onset of the Miocene Climatic Optimum. *Geology* 43:123–126, https://doi.org/10.1130/G36317.1.

Holbourn, A.E., W. Kuhnt, S.C. Clemens, K.G.D. Kochhann, J. Jöhnck, J. Lübbers, and N. Andersen. 2018. Late Miocene climate cooling and intensification of southeast Asian winter monsoon. *Nature Communications* 9:1584, https://doi.org/10.1038/s41467-018-03950-1.

Imbrie, J., J.D. Hay, D.G. Martinson, A. McIntyre, A.C. Mix, J.J. Morley, N.G. Pisias, W.L. Prell, and N.J. Shackleton. 1984. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record. Pp. 269–305 in *Milankovitch and Climate: Understanding the Response to Astronomical Forcing.* Proceedings of the NATO Advanced Research Workshop held November 30–December, 4, 1982, in Palisades, NY, A. Berger, J. Imbrie, H. Hays, G. Kukla, and B. Saltzman, eds, D. Reidel Publishing, Dordrecht.

Laskar, J., P. Robutel, F. Joutel, M. Gastineau, A.C.M. Correia, B. Levrard. 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astronomy & Astrophysics* 428(1):261–285, https://doi.org/10.1051/0004-6361:20041335.

Lauretano, V., K. Littler, M. Polling, J.C. Zachos, and L.J. Lourens. 2015. Frequency, magnitude and character of hyperthermal events at the onset of the Early Eocene Climatic Optimum. *Climates of the Past* 11:1,313–1,324, https://doi.org/10.5194/cp-11-1313-2015.

Lauretano, V., F.J. Hilgen, J.C. Zachos, L.J. Lourens. 2016. Astronomically tuned age model for the early Eocene carbon isotope events: A new high-resolution $\delta^{13}C$ benthic record of ODP Site 1263 between ~49 and ~54 Ma. *Newsletters on Stratigraphy* 49(2):383–400, https://doi.org/10.1127/nos/2016/0077.

Lauretano, V., J.C. Zachos, and L.J. Lourens. 2018. Orbitally paced carbon and deep-sea temperature changes at the peak of the Early Eocene Climatic Optimum. *Paleoceanography and Paleoclimatology* 33, https://doi.org/10.1029/2018PA003422.

Liebrand, D., H.M. Beddow, L.J., Lourens, H. Pälike, I. Raffi, S.M. Bohaty, F.J. Hilgen, M.J.M. Saes, P.A. Wilson, A.E. van Dijk, and others. 2016. Cyclostratigraphy and eccentricity tuning of the early Oligocene through early Miocene (30.1–17.1 Ma): *Cibicides mundulus* stable oxygen and carbon isotope records from Walvis Ridge Site 1264. *Earth and Planetary Science Letters* 450:392–405, https://doi.org/10.1016/j.epsl.2016.06.007.

Liebrand, D., A.T.M. de Bakker, H.M. Beddow, P.A. Wilson, S.M. Bohaty, G. Ruessink, H. Pälike, S.J. Batenburg, F.J. Hilgen, D.A. Hodell, and others. 2017. Evolution of the early Antarctic ice ages. *Proceedings of the National Academy of Sciences of the United States of America* 114(15):3,867–3,872, https://doi.org/10.1073/pnas.1615440114.

Littler, K., U. Röhl, T. Westerhold, and J.C. Zachos. 2014. A high-resolution benthic stable-isotope record for the South Atlantic: Implications for orbital-scale changes in Late Paleocene–Early Eocene climate and carbon cycling. *Earth and Planetary Science Letters* 401:18–30, https://doi.org/10.1016/j.epsl.2014.05.054.

Lisiecki, L.E., and M.E. Raymo. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography* 20, PA1003, https://doi.org/10.1029/2004PA001071.

Lisiecki, L.E., and M.E. Raymo. 2007. Plio-Pleistocene climate evolution: Trends and transitions in glacial cycle dynamics. *Quaternary Science Reviews* 26:56–69, https://doi.org/10.1016/j.quascirev.2006.09.005.

Milankovitch, M.M. 1941. *Canon of Insolation and the Ice-Age Problem*. Royal Serbian Academy, Belgrade. [English translation by the Israel Program for Scientific Translations, published for the United States Department of Commerce and the National Science Foundation, Washington, DC.]

Pälike, H., J. Frazier, and J.C. Zachos. 2006a. Extended orbitally forced palaeoclimatic records from the equatorial Atlantic Ceara Rise. *Quaternary Science Reviews* 25(23):3,138–3,149, https://doi.org/10.1016/j.quascirev.2006.02.011.

Pälike, H., R.D. Norris, J.O. Herrle, P.A. Wilson, H.K. Coxall, C.H. Lear, N.J. Shackleton, A.K. Tripati, and B.S. Wade. 2006b. The heartbeat of the Oligocene climate system. *Science* 314:1,894–1,898, https://doi.org/10.1126/science.1133822.

Sexton, P.F., R.D. Norris, P.A. Wilson, H. Pälike, T. Westerhold, U. Röhl, C.T. Bolton, and S. Gibbs. 2011. Eocene global warming events driven by ventilation of oceanic dissolved organic carbon. *Nature* 471:349–352, https://doi.org/10.1038/nature09826.

Shackleton, N.J., and S. Crowhurst. 1997. Sediment fluxes based on an orbitally tuned time scale 5 Ma to 14 Ma, Site 926. Pp. 69–82 in *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 154, N.J. Shackleton, W.W. Curry, C. Richter, and T. Bralower, eds, College Station, TX.

Shackleton, N.J., S.J. Crowhurst, G.P. Weedon, and J. Laskar. 1999. Astronomical calibration of Oligocene–Miocene time. *Philosophical Transactions of the Royal Society A* 357(1757), https://doi.org/10.1098/rsta.1999.0407.

Stap, L., L.J. Lourens, E. Thomas, A. Sluijs, S. Bohaty, and J.C. Zachos. 2010. High-resolution deep-sea carbon and oxygen isotope records of Eocene Thermal Maximum 2 and H2. *Geology* 38(7):607–610, https://doi.org/10.1130/G30777.1.

Tian, J., M. Yang, M.W. Lyle, R. Wilkens, and J.K. Shackford. 2013. Obliquity and long eccentricity pacing of the Middle Miocene climate transition. *Geochemistry, Geophysics, Geosystems* 14:1,740–1,755, https://doi.org/10.1002/ggge.20108.

Vahlenkamp, M., I. Niezgodzki, D. De Vleeschouwer, T. Bickert, D. Harper, S. Kirtland Turner, G. Lohmann, P.F. Sexton, J.C. Zachos, and H. Pälike. 2018. Astronomically paced changes in deep-water circulation in the western North Atlantic during the middle Eocene. *Earth and Planetary Science Letters* 484:329–340, https://doi.org/10.1016/j.epsl.2017.12.016.

van Peer, T.E., C. Xuan, P.C., Lippert, D. Liebrand, C. Agnini, and P.A. Wilson. 2017. Extracting a detailed magnetostratigraphy from weakly magnetized, Oligocene to Early Miocene sediment drifts recovered at IODP Site U1406 (Newfoundland Margin, northwest Atlantic Ocean). *Geochemistry, Geophysics, Geosystems* 18(11):3,910–3,928, https://doi.org/10.1002/2017GC007185.

Westerhold, T., U. Röhl, B. Donner, H.K. McCarren, and J.C. Zachos. 2011. A complete high-resolution Paleocene benthic stable isotope record for the central Pacific (ODP Site 1209). *Paleoceanography* 26(2), https://doi.org/10.1029/2010PA002092.

Westerhold, T., U Röhl, H. Pälike, R. Wilkens, P.A. Wilson, and G. Acton. 2014. Orbitally tuned timescale and astronomical forcing in the middle Eocene to early Oligocene. *Climates of the Past* 10:955–973, https://doi.org/10.5194/cp-10-955-2014.

Westerhold, T., U. Röhl, T. Frederichs, C. Agnini, I. Raffi, J.C. Zachos, and R.H. Wilkens. 2017. Astronomical calibration of the Ypresian timescale: Implications for seafloor spreading rates and the chaotic behavior of the solar system? *Climates of the Past* 13:1,129–1,152, https://doi.org/10.5194/cp-13-1129-2017.

Westerhold, T., U. Röhl, B. Donner, and J.C. Zachos. 2018. Global extent of Early Eocene hyperthermal events: A new Pacific benthic foraminiferal isotope record from Shatsky Rise (ODP Site 1209). *Paleoceanography and Paleoclimatology* 33(6):626–642, https://doi.org/10.1029/2017PA003306.

Wilkens, R.H., T. Westerhold, A.J. Drury, M. Lyle, T. Gorgas, and J. Tian. 2017. Revisiting the Ceara Rise, equatorial Atlantic Ocean: Isotope stratigraphy of ODP Leg 154 from 0 to 5 Ma. *Climates of the Past* 13:779–793, https://doi.org/10.5194/cp-13-779-2017.

Woodard, S.C., Y. Rosenthal, K.G. Miller, J.D. Wright, B.K. Chiu, and K.T. Lawrence. 2014. Antarctic role in Northern Hemisphere glaciation. *Science* 346:847, https://doi.org/10.1126/science.1255586.

Zachos, J.C., N.J., Shackleton, J.S. Revenaugh, H. Pälike, and B.P. Flower. 2001. Climate response to orbital forcing across the Oligocene-Miocene boundary. *Science* 292:274–278, https://doi.org/10.1126/science.1058288.

Zachos, J.C., G.R. Dickens, and R.E. Zeebe. 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* 451(7176):279–283, https://doi.org/10.1038/nature06588.

Zachos, J.C., H. McCarren, B. Murphy, U. Röhl, and T. Westerhold. 2010. Tempo and scale of late Paleocene and early Eocene carbon isotope cycles: Implications for the origin of hyperthermals. *Earth and Planetary Science Letters* 299(1):242–249, https://doi.org/10.1016/j.epsl.2010.09.004.

Zeeden, C., F. Hilgen, T. Westerhold, L.J. Lourens, U. Röhl, and T. Bickert. 2013. Revised Miocene splice, astronomical tuning and calcareous plankton biochronology of ODP Site 926 between 5 and 14.4 Ma. *Palaeogeography, Palaeoclimatology, Palaeoecology* 369:430–451, https://doi.org/10.1016/j.palaeo.2012.11.009.

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