

# Triassic–Jurassic climate in continental high-latitude Asia was dominated by obliquity-paced variations (Junggar Basin, Ürümqi, China)

Jingeng Sha<sup>a,1</sup>, Paul E. Olsen<sup>b,1</sup>, Yanhong Pan<sup>a</sup>, Daoyi Xu<sup>c</sup>, Yaqiang Wang<sup>a</sup>, Xiaolin Zhang<sup>d</sup>, Xiaogang Yao<sup>a</sup>, and Vivi Vajda<sup>e,f</sup>

<sup>a</sup>State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Nanjing 210008, China; <sup>b</sup>Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10968; <sup>c</sup>Institute of Geology, China Earthquake Administration, Beijing 100029, China; <sup>d</sup>Chinese Academy of Sciences Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China; <sup>e</sup>Department of Geology, Lund University, 223 62 Lund, Sweden; and <sup>f</sup>Department of Palaeobiology, Swedish Museum of Natural History, 104 05 Stockholm, Sweden

Contributed by Paul E. Olsen, January 18, 2015 (sent for review December 19, 2014; reviewed by Linda A. Hinnov and Michael R. Rampino)

**Empirical constraints on orbital gravitational solutions for the Solar System can be derived from the Earth's geological record of past climates. Lithologically based paleoclimate data from the thick, coal-bearing, fluvial-lacustrine sequences of the Junggar Basin of Northwestern China (paleolatitude ~60°) show that climate variability of the warm and glacier-free high latitudes of the latest Triassic–Early Jurassic (~198–202 Ma) Pangea was strongly paced by obliquity-dominated (~40 ky) orbital cyclicity, based on an age model using the 405-ky cycle of eccentricity. In contrast, coeval low-latitude continental climate was much more strongly paced by climatic precession, with virtually no hint of obliquity. Although this previously unknown obliquity dominance at high latitude is not necessarily unexpected in a high CO<sub>2</sub> world, these data deviate substantially from published orbital solutions in period and amplitude for eccentricity cycles greater than 405 ky, consistent with chaotic diffusion of the Solar System. In contrast, there are indications that the Earth–Mars orbital resonance was in today's 2-to-1 ratio of eccentricity to inclination. These empirical data underscore the need for temporally comprehensive, highly reliable data, as well as new gravitational solutions fitting those data.**

orbital forcing | obliquity cycle | Triassic–Jurassic | lacustrine sediments | solar system chaos

Our understanding of Triassic and Early Jurassic high-latitude climate, biotic evolution, mass extinction, and geochronology is very poor in contrast to that of the contemporaneous tropics (1, 2). This poor resolution impairs an elucidation of the basic patterns of Earth system function during the early Mesozoic, notably the high-latitude climatic response to orbital forcing, as well as the effects of the eruption of the Triassic–Jurassic Central Atlantic Igneous Province (CAMP) (3). The former issue bears on the stability of the Solar System, in which determining variations in orbital eccentricity (via climatic precession) and inclination (via obliquity) figure as crucial (4–6), and the latter bears on the causes, effects, and recovery from the end-Triassic mass extinction (ETE) (e.g., ref. 2). Here, we describe results of a cyclostratigraphic investigation of lithologic variations in the paleo-high latitude, lacustrine, Late Triassic–Early Jurassic Haojiagou and Badaowan formations of the Junggar Basin, China representing, to our knowledge, the first analysis of orbital cyclicity from a high-latitude, early Mesozoic continental sequence, and a step toward development of an empirical basis for evaluating numerical solutions of Solar System chaotic behavior.

## Junggar Basin, Ürümqi, Western China

The thick, nonmarine, early Mesozoic sequence of the Junggar Basin of Western China (Fig. 1 and Figs. S1 and S2) comprises >11 km of largely nonmarine Late Paleozoic to Cenozoic strata deposited in the northwestern-most of the “walled basins” of China (7).

It is a collisional successor basin, established during the Late Permian, 50–75 My after the cessation of subduction and complex amalgamation of microplates and ocean basins. Triassic and Early Jurassic age strata amount to 3,600 m in the interior, subsurface region of the basin (7) but outcrop extensively in several areas. One of the largest outcrops is the Haojiagou section located about 50 km southwest of Ürümqi City on the southern margin of the Junggar Basin of northern Xinjiang Uygur (Uighur) Autonomous Region, Northwestern China (Fig. 1 and Fig. S1) that forms the basis for this report. There, the 1,050 m of the nonmarine Haojiagou and coal-bearing Badaowan formations are continuously exposed and only slightly deformed (Fig. S2). The section has been studied in various aspects (e.g., see *SI Text*), but only one summary on the cyclostratigraphy has been published to date (8).

The paleolatitude of the Junggar Basin for the Triassic–Jurassic is most parsimoniously placed at about 60° N (Fig. 1), constrained by paleomagnetic data (9) interpreted in light of the effects of compaction-induced inclination error (10) and plate-tectonic context (e.g., ref. 7; see *SI Text*). It is the highest latitude continental basin in which Triassic–Jurassic orbitally paced cyclicity has been quantitatively examined.

## Significance

**Geological records of paleoclimate provide the only constraints on Solar System orbital solutions extending beyond the ~50-Ma limit imposed by chaotic diffusion. Examples of such constraints are coupled high and low latitude, Triassic–Jurassic (~198–202 Ma) sedimentary cyclicity in coal-bearing outcrops from the ~60° N-paleolatitude Junggar Basin (Western China), and contemporaneous tropical basins. Analysis reveals climate variability dominated by obliquity-scale cyclicity in the Junggar Basin and precession-scale cyclicity in the tropics. Together, these geological records empirically constrain orbital solutions by providing joint  $g_4 - g_3$  and  $s_4 - s_3$  secular frequency estimates of the Earth–Mars orbital resonance. These results demonstrate the opportunity for developing a new class of solutions grounded by geological data extending hundreds of millions of years into the geologic past.**

Author contributions: J.S., P.E.O., and D.X. designed research; J.S., P.E.O., Y.P., Y.W., X.Z., X.Y., and V.V. performed research; J.S., P.E.O., D.X., and V.V. analyzed data; P.E.O. wrote the paper; J.S. was the leader of expeditions to Ürümqi and helped write the paper; Y.P., Y.W., X.Z., and X.Y. collected data; and V.V. analyzed samples.

Reviewers: L.A.H., Johns Hopkins University; and M.R.R., New York University.

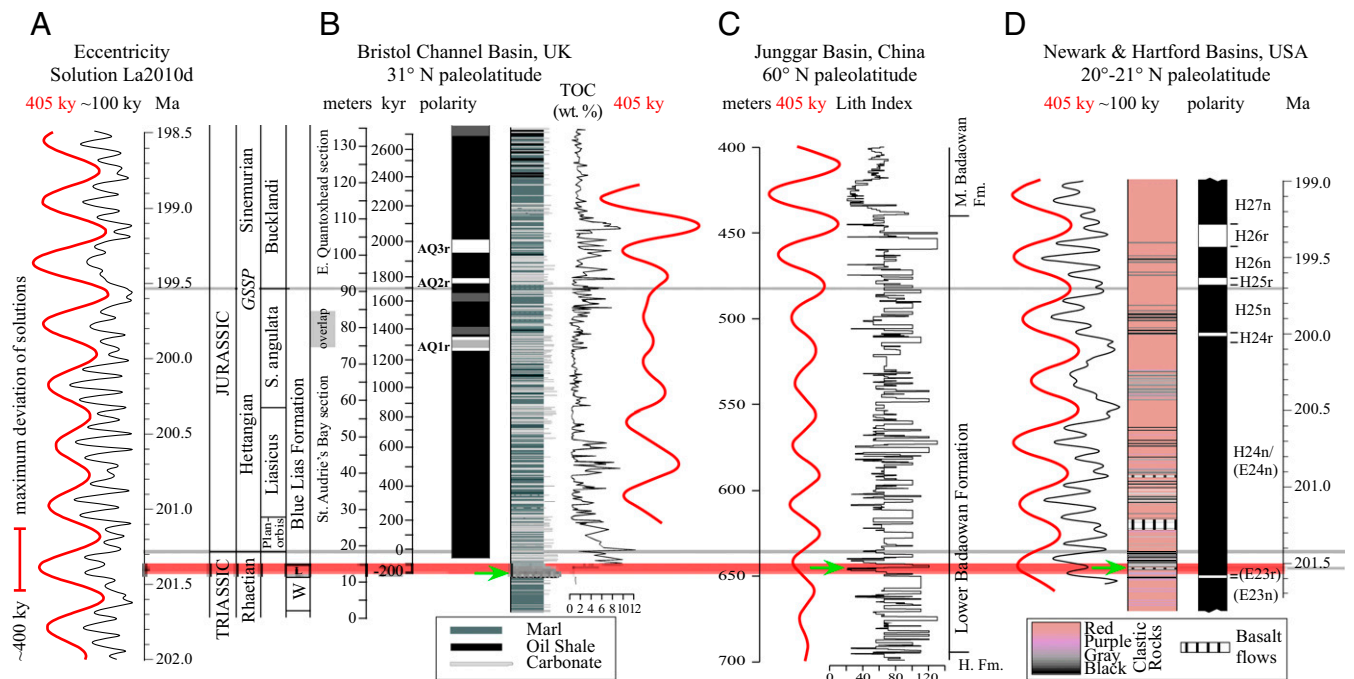
The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

<sup>1</sup>To whom correspondence may be addressed. Email: polsen@ldeo.columbia.edu or jgsha@nigpas.ac.cn.

This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1501137112/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1501137112/-DCSupplemental).





**Fig. 2.** LITH Index data (C) and correlative sections: (A) Laskar 2010d solution (21); (B) Bristol Channel (United Kingdom); (C) Junggar Basin (China); (D) the Newark–Hartford astrochronology and geomagnetic polarity time scale (APTS). The thick red bar indicates the interval of extinctions and uncertainty of correlations between the sections, and the green arrows indicate the last appearance of *L. rhaeticus* (SI Text). A and B are adapted from refs. 19 and 31 (potential error added from ref. 21); D is modified from refs. 25 and 26. Note the difference in phase between the phasing eccentricity cycles in the La2010d solution (selected by ref. 31 for comparison with B) and the geological data that we attribute to chaotic drift; therefore, we have retained the independent times scales for both A and D.

the middle of the 20- to 40-m range of the fluctuating band of high amplitude in the wavelet spectra (Fig. 4 and Fig. S4).

Assuming that we have correctly identified the 405-ky cycle in the LITH index depth series, the most prominent higher frequency cycles of the Haojiagou and lower Badaowan formations have spectral peaks with periods of between 30 ky and 60 ky, with the median periods most strongly at 42.5 and 44.6 ky. These periods are close to what would be expected for the obliquity periods, which for the Triassic–Jurassic should be 36.6 and 46.7 ky (6, 27, 28), assuming a constant rate of recession of the moon and constant dynamic ellipticity of the Earth, with the former period being of much higher magnitude. The shift to lower frequencies from the expected precession and obliquity periods is also observed in the precession band in the eastern North American Triassic Locketong Formation where the shift has been interpreted as a consequence of accumulation rate variability (22, 24). The most dramatic expression of such a frequency-modulated shift would be occasional and perhaps periodically spaced hiatuses as might be present in the fluvial portions of the Junggar sequences. However, it is not impossible that the unexpectedly low frequencies could be real, caused by nonlinear changes through time in dynamic ellipticity that could produce occasional decreases in precession rate (20, 29). Nonetheless, because the independently U–Pb–calibrated (2) periods of Newark Basin latest Triassic–Early Jurassic precession-band cycles are compatible with an average period of about 20 ky, spectral distortion from frequency modulation is the simpler explanation for the apparent discrepancy. Relatively less important in the analysis are periods that could be assigned to climatic precession although significant periods are present in the MTM analyses. The weakness in amplitude at precessional periods could be a real feature of the climate system of the Mesozoic (see *Mesozoic High- vs. Low-Latitude Cyclicity*) or it could be due to accumulation rate noise at the precessional frequencies. Periods at about 100 ky, although present, are weak, consistent with the low power of the assumed precession

periods, but, because we seem to be able to recognize the 405-ky cycle, some climatic precession signal is evidently present.

Based on our analysis of thickness periodicities, the sedimentary cycles attributed to climatic precession, obliquity, and eccentricity cycles correspond to the microcycles and different scales of mesoscale cycles of Hornung and Hinderer (14). These Junggar Basin strata are similar to what Olsen and Kent (30) termed Kap Stewart-type lacustrine sequences, named after the eponymous gray and black cyclical strata of Jamesonland East Greenland (16). We propose that the cycles in these sequences fit into a continuum of orbitally forced lacustrine sedimentary cycles extending from the tropics to the high latitudes, with the Haojiagou and Badaowan cycles in Kap Stewart-type lacustrine sequences representing the humid high latitude end member of the cyclicity (30). This type of lacustrine sequence and cycles may well extend to the paleo-north pole, for which there is obviously no sedimentary analog today.

### Testing the Junggar Basin Age Model

Direct age calibration of the section by radiometric or paleomagnetic means does not yet exist for the Triassic–Jurassic of the Junggar Basin; however, the age model may be at least partially tested by its consistency with contemporaneous records from elsewhere, specifically the Newark–Hartford basins of eastern North America, the Bristol Channel Basin of the United Kingdom, and the Pucara Basin of Peru (Fig. 1, Fig. S3, and Table 1).

To compare the obliquity-dominated successions of the Junggar Basin with the precession-dominated eastern North American lacustrine sequences and the contemporaneous marine section at St. Audrie’s Bay in the United Kingdom (Bristol Channel Basin), we compared the filtered 405-ky cycle from the three sections (SI Text) and correlated them using the last appearance of *Lunatisporites rhaeticus* (green arrows in Fig. 2). Using the latter datum results in the encouraging observation that the 405-ky cycles are in phase and that the interval of low



**Table 1. U-Pb and astrochronological ages compared**

Boundary or unit	Newark igneous*	Newark–Hartford*	Pucara Basin	Bristol Channel† Pucara‡/Newark§
Hettangian–Sinemurian boundary	—	199.70 ± 0.02	199.46 ± 0.17	199.61/199.66
Hook Mountain Basalt	200.916 ± 0.064	200.93 ± 0.02	—	—
Preakness Basalt	201.274 ± 0.032	201.28 ± 0.02	—	—
Rhaetian–Hettangian boundary	—	201.42 ± 0.022	201.36 ± 0.14‡	201.32/201.37
Orange Mountain Basalt	201.520 ± 0.034	201.52 ± 0.02	—	—
End-Triassic extinction	201.564 ± 0.015	201.56 ± 0.02	201.51 ± 0.15	201.51/201.56

\*See ref. 2 for ages. Details in Table S2.

†See refs. 19 and 31 for ages. Details in Table S2.

‡See refs. 12 and 17 for ages. Details in Table S2.

§See ref. 15 for ages. Details in Table S2.

configuration with Pangea straddling the equator, a lack of polar glaciers (35), and very high CO<sub>2</sub> (approximate background at between 1,000 and 2,000 ppm and maxima of >6,000 ppm) (36)—a world without modern analog. Therefore, explanations of obliquity dominance due to fluctuations of high-latitude glaciers are difficult to support for the early Mesozoic. However, some aspects of these explanations might still be pertinent to the Haojiagou and Badaowan formations. In particular, integrated summer insolation is directly controlled by obliquity and has been proposed as a cause of the late Neogene obliquity dominance in glacial fluctuations (32), and it is possible that the highly vegetated Triassic–Jurassic high latitudes were similarly sensitive to the length of the growing season and associated timing and magnitude of precipitation and evaporation.

### Implications for Chaotic Evolution of the Solar System and Astronomical Solutions

Since Poincaré's (37) contribution to dynamical systems, it has been recognized that the Solar System has chaotic properties. Chaos significantly limits the accuracy of numerical solutions of planetary behavior, including the frequency and phases of climatically important orbital cycles (4–6), and impedes understanding of the general problem of the stability of the Solar System (5, 13). At time scales of hundreds of millions of years, chaotic diffusion of the gravitational system of the Solar System results in an inability to recognize accurate solutions of planetary orbital and axial behavior (4).

Integral to the long-term chaotic behavior of the Solar System are the secular resonances of the planets, particularly for the inner Solar System. Particularly important are those of Earth and Mars (4), affecting modulations of eccentricity and obliquity with present periods of 2.4 and 1.2 My ( $g_4 - g_3$  and  $s_4 - s_3$ , respectively, where  $g_4$  and  $g_3$  are related to the precession of the orbital perihelia of Mars and Earth and  $s_4$  and  $s_3$  are related to orbital inclination). However, due to chaotic diffusion of the gravitational system, these periods are expected to change through time. Presently, there is a two-to-one ratio of the eccentricity modulator (2.4 My) to the obliquity modulator (1.2 My), reflecting the secular resonant argument  $2(s_4 - s_3) - (g_4 - g_3) = 0$ , which is currently in libration. However, there are expected to be important transitions in the chaotic behavior of the gravitational system from libration to circulation so that the eccentricity and obliquity modulators are equal ( $s_4 - s_3) - (g_4 - g_3) = 0$  (38). Because both the period and state of these modulating cycles have varied in an unknown way in deep time, strict interpretation of insolation curves are unreliable beyond about 50 Ma (20, 21). This uncertainty is most obviously reflected in the eccentricity and obliquity modulating cycles with periods longer than 405 ky and the long-term phase relationships of all of the cycles. Without geological data with a long obliquity record, it is not possible to determine when these transitions in the Earth–Mars resonances

occur or even if they occur, or what the periods of the long eccentricity or inclination cycles should be.

In addition to being a celestial mechanical problem, chaotic drift in the gravitational solutions also poses fundamental Earth science problems because it limits tuning of geological records to insolation curves and our ability to use astrochronologies to assess and improve the accuracy of important isotopic dating systems (e.g., ref. 39). Empirical, deep-time geological data have the potential to allow us to determine which solutions best fit the actual history of the Solar System.

To quantify the actual behavior of the celestial mechanical gravitational system, precession-related (eccentricity) and obliquity-related cycles need to be isolated in geological records. Continental records, which tend to be tightly coupled to local forcing, provide a possible mechanism to isolate precession-related eccentricity cycles, dominant at low latitudes, from the obliquity-related cyclicity important at higher latitudes.

Previous quantitative investigations of long Late Triassic–Early Jurassic records have been limited to the lower latitudes, largely the tropics and subtropics in eastern North America (2, 22, 24, 25) and the United Kingdom (e.g., refs. 19 and 40). In these areas (20°–30° N) (10), the effects of obliquity on local climate forcing would be expected to be small compared with the higher latitudes, as predicted by basic astronomical theory, although precessional effects should always be greatest in insolation at all latitudes, and that is what is observed for the Triassic–Jurassic in the records described thus far. In the case of the tropical records in eastern North America, obliquity was barely detected (22, 24), but a strong 1.6- to 1.8-My cycle in eccentricity ( $g_4 - g_3$ ) is present, differing from the present 2.4 My presumably because of chaotic diffusion (6, 24). More or less the same value of the  $g_4 - g_3$  cycle, in the same phase, is present in the contemporaneous tropical pelagic cherts from the Panthalassic Ocean at Inuyama, Japan (41).

Until now, there have been no long Triassic–Jurassic, high-latitude records that have been quantitatively analyzed, and therefore we have had little knowledge of what the quantitative obliquity behavior was, especially with regard to their modulating cycles. Importantly, there is a strong suggestion of modulation of the obliquity by an ~819-ky (~70-m) cycle in the upper Haojiagou and lower Badaowan, visible in the wavelet spectrum (Fig. 3 and Fig. S4) where it is evident as a modulation in the strength of obliquity cycle (Fig. S4), both as filtered and demodulated data (Figs. S5–S7), and also as period in its own right (Fig. S4). This period is missing or extremely weak in the tropical continental records (22, 24). Together, the data from the Junggar Basin, Newark–Hartford basins, and St. Audrie's Bay section suggest the present-day two-to-one ratio (Early Jurassic, ~1.6–0.8 My) of orbital eccentricity to inclination for the state of the Earth–Mars resonance, but with different periods and phases not seen in existing orbital solutions (21) (Fig. 2).

## Conclusions

Analysis of the LITH proxy of environmental change shows that an astronomical signal in which obliquity is dominant can be extracted from lacustrine strata of the high-latitude ( $\sim 60^\circ$  N) Junggar Basin straddling the end-Triassic extinction and Triassic–Jurassic boundary. Constrained by fixing the accumulation rate to the 405-ky eccentricity cycle, data show that the main periods of obliquity for the Late Triassic–Early Jurassic are present and were dominant components of high-latitude Early Mesozoic climate, dramatically different from the climatic precession-dominated continental tropics. In combination, the data are incompatible with published astronomical solutions for the Triassic–Jurassic in phase and amplitude, consistent with chaotic behavior of the Solar System whereas, at the same time, the Earth–Mars orbital resonance seems to have been in today’s two-to-one ratio of eccentricity to inclination, providing a constraint for the Earth–Mars secular resonance for around 201 Ma. With the prospect of the acquisition of better temporally resolved records from deeper lake settings in the Junggar and other basins, the use of more directly climate-sensitive proxies, and additional exploration of the paleobiological context of the strata, it will be possible to test these findings, constraining the history of Solar System chaos, during this transitional time in Earth history.

## Methods

LITH index data were recorded during the 1996, 1998, and 2008 field seasons using standard descriptive field methods. Standard preparation procedures were used to prepare the palynological slides, archived at the Department of Geology, Lund University, Sweden. The evolutive FFT and MTM spectra were developed using Analyseries (2.0) (42), and the evolutive wavelet spectra were computed using the Matlab script of Torrence and Compo (43). See *SI Text* for additional methodological details.

**ACKNOWLEDGMENTS.** We thank Deng Shenghui for helpful comments in the field and on the manuscript and Dennis Kent for help in interpreting the paleolatitude of the basin. We are grateful to Ji Xuefeng and Cheng Xiansheng, who guided us in fieldwork and shared significant unpublished information. We thank Christopher Scotese for help in producing the reconstruction of Pangea in Fig. 1. The manuscript was reviewed by Linda Hinnov and Michael Rampino, who provided many useful suggestions. Research was supported by the National Basic Research Program of China (973 Program 2012CB821906), the Strategic Priority Research Program (B) (Chinese Academy of Sciences XDB03010101), National Natural Science Foundation of China (91114201), Bureau of Geological Survey of China, the National Committee of Stratigraphy of China, and the Linnaeus Centre, Lund University Carbon Cycle Centre (LUCCI) funded through the Swedish Research Council (349-2007-8705). This article is a contribution to United Nations Educational, Scientific and Cultural Organization–International Union of Geological Sciences–International Geoscience Programme (UNESCO-IUGS-IGCP) Project 632.

- Irmis RB, Whiteside JH (2010) Newly integrated approaches to studying Late Triassic terrestrial ecosystems. *Palaios* 25:689–691.
- Blackburn TJ, et al. (2013) Zircon U–Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province. *Science* 340(6135):941–945.
- Marzoli A, et al. (1999) Extensive 200-million-year-old continental flood basalts of the central Atlantic magmatic province. *Science* 284(5414):616–618.
- Laskar J (1999) The limits of Earth orbital calculations for geological time-scale use. *Phil Trans R Soc Lond A* 357(1757):1735–1759.
- Laskar J (2013) Is the Solar System stable? *Chaos* 2013:239–270.
- Hinnov LA (2013) Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *Geol Soc Am Bull* 125(11–12):1703–1734.
- Carroll AR, Graham SA, Smith ME (2010) Walled sedimentary basins of China. *Basin Res* 22(1):17–32.
- Sha J, et al. (2010) Astronomical calibrated time intervals for the non-marine Badaowan Formation, Lower Jurassic in Haojiagou of Ürümqi City, Western China. *Earth Sci Front* 17(Special Issue):22–23.
- Choulet F, et al. (2013) First Triassic palaeomagnetic constraints from Junggar (NW China) and their implications for the Mesozoic tectonics in Central Asia. *J Asian Earth Sci* 78:371–394.
- Kent DV, Tauxe L (2005) Corrected Late Triassic latitudes for continents adjacent to the North Atlantic. *Science* 307(5707):240–244.
- Willis KJ, McElwain JC (2002) *The Evolution of Plants* (Oxford Univ Press, New York).
- Gueex J, et al. (2012) Geochronological constraints on post-extinction recovery of the ammonoids and carbon cycle perturbations during the Early Jurassic. *Palaeogeogr Palaeoclimatol Palaeoecol* 346–347:1–11.
- van Vugt N, Langereis CG, Hilgen FJ (2001) Orbital forcing in Pliocene–Pleistocene Mediterranean lacustrine deposits: Dominant expression of eccentricity versus precession. *Palaeogeogr Palaeoclimatol Palaeoecol* 172:193–205.
- Hornung J, Hinderer M (2011) Depositional dynamics and preservation potential in a progradational lacustrine fluvio-deltaic setting: Implications for high-resolution sequence stratigraphy (Upper Triassic, Northwestern China). *From River to Rock Record: The Preservation of Fluvial Sediments and Their Subsequent Interpretation*, eds Davidson SK, Leleu S, North CP (SEPM Society for Sedimentary Geology, Tulsa OK), SEPM Special Publication No. 97, pp. 281–310.
- Whiteside JH, et al. (2011) Pangean great lake palaeoecology on the cusp of the end-Triassic extinction. *Palaeogeogr Palaeoclimatol Palaeoecol* 301(1–4):1–17.
- Dam G, Surlyk F (1992) Forced regressions in a large wave-dominated and storm-dominated anoxic lake, Rhaetian–Sinemurian Kap Stewart Formation, East Greenland. *Geology* 20:749–752.
- Wotzlav J-F, et al. (2014) Towards accurate numerical calibration of the Late Triassic: High-precision U–Pb geochronology constraints on the duration of the Rhaetian. *Geology* 42:571–574.
- Whiteside JH, Olsen PE, Eglinton T, Brookfield ME, Sambrotto RN (2010) Compound-specific carbon isotopes from Earth’s largest flood basalt eruptions directly linked to the end-Triassic mass extinction. *Proc Natl Acad Sci USA* 107(15):6721–6725.
- Ruhl M, et al. (2010) Astronomical constraints on the duration of the early Jurassic Hettangian stage and recovery rates following the end-Triassic mass extinction (St. Audrie’s Bay/East Quantoxhead, UK). *Earth Planet Sci Lett* 295:262–276.
- Laskar J, et al. (2004) A long-term numerical solution for the insolation quantities of the Earth. *Astron Astrophys* 428:261–285.
- Laskar J, Fienga A, Gastineau M, Manche H (2011) La2010: A new orbital solution for the long-term motion of the Earth. *Astron Astrophys* 532:A89.
- Olsen PE, Kent DV (1996) Milankovitch climate forcing in the tropics of Pangea during the Late Triassic. *Palaeogeogr Palaeoclimatol Palaeoecol* 122:1–26.
- Kent DV, Olsen PE (1999) Astronomically tuned geomagnetic polarity time scale for the Late Triassic. *J Geophys Res* 104:12,831–12,841.
- Olsen PE, Kent DV (1999) Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the early Mesozoic time scale and the long-term behavior of the planets. *Philos Trans R Soc Lond* 357:1761–1787.
- Whiteside JH, Olsen PE, Kent DV, Fowell SJ, Et-Touhami M (2007) Synchrony between the CAMP and the Triassic–Jurassic mass-extinction event? *Palaeogeogr Palaeoclimatol Palaeoecol* 244(1–4):345–367.
- Kent DV, Olsen PE (2008) Early Jurassic magnetostratigraphy and paleolatitudes from the Hartford continental rift basin (eastern North America): Testing for polarity bias and abrupt polar wander in association with the central Atlantic magmatic province. *J Geophys Res* 113:B06105.
- Berger A, Loutre MF, Laskar J (1992) Stability of the astronomical frequencies over the Earth’s history for paleoclimate studies. *Science* 255(5044):560–566.
- Olsen PE, Whiteside JH (2008) Pre-Quaternary Milankovitch cycles and climate variability. *Encyclopedia of Paleoclimatology and Ancient Environments*, Earth Science Series, ed Gornitz V (Kluwer Academic Publishers, Dordrecht, The Netherlands), pp 826–835.
- Morrow E, Mitrovica JX, Forte AM, Glišović P, Huybers P (2012) An enigma in estimates of the Earth’s dynamic ellipticity. *Geophys J Int* 191:1129–1134.
- Olsen PE, Kent DV (2000) High resolution early Mesozoic Pangean climatic transect in lacustrine environments. *Epicontinental Triassic, Volume 3*, eds Bachmann G, Lerche I (Zentralblatt für Geologie und Paläontologie VIII) (Schweizerbart Science Publishers, Stuttgart), pp 1475–1496.
- Hüsing SK, et al. (2014) Astronomically-calibrated magnetostratigraphy of the Lower Jurassic marine successions at St. Audrie’s Bay and East Quantoxhead (Hettangian–Sinemurian; Somerset, UK). *Palaeogeogr Palaeoclimatol Palaeoecol* 403:43–56.
- Huybers P (2006) Early Pleistocene glacial cycles and the integrated summer insolation forcing. *Science* 313(5786):508–511.
- Raymo ME, Nisancioglu K (2003) The 41kyr world: Milankovitch’s other unsolved mystery. *Paleoceanography* 18:PA1011.
- Prokopenko AA, Hinnov LA, Williams DF, Kuzmin MI (2006) Orbital forcing of continental climate during the Pleistocene: A complete astronomically tuned climatic record from Lake Baikal, SE Siberia. *Quat Sci Rev* 25:3431–3457.
- Frakes LA, Francis JE, Sykyus JL (1992) *Climate Modes of the Phanerozoic* (Cambridge Univ Press, Cambridge, UK).
- Schaller MF, Wright JD, Kent DV (2011) Atmospheric PCO<sub>2</sub> perturbations associated with the Central Atlantic Magmatic Province. *Science* 331(6023):1404–1409.
- Poincaré H (1892–1899) *Les Méthodes Nouvelles de la Mécanique Céleste* (Gauthier-Villars, Paris), Vol I–III, reprinted by Blanchard, 1987.
- Laskar J (2003) Chaos in the Solar System. *Ann Henri Poincaré* 4(Suppl 2):S693–S705.
- Kuiper KF, et al. (2008) Synchronizing rock clocks of Earth history. *Science* 320(5875):500–504.
- Kemp DB, Coe AL (2007) A nonmarine record of eccentricity forcing through the Upper Triassic of southwest England and its correlation with the Newark Basin astronomically calibrated geomagnetic polarity time scale from North America. *Geology* 35(11):991–994.
- Ikedo M, Tada R (2013) Long period astronomical cycles from the Triassic to Jurassic bedded chert sequence (Inuyama, Japan): Geologic evidences for the chaotic behavior of solar planets. *Earth Planets Space* 65:351–360.
- Paillard D, Labeyrie L, Yiou P (1996) Macintosh program performs time-series analysis. *Eos Trans AGU* 77:379.
- Torrence C, Compo GP (1998) A practical guide to wavelet analysis. *Bull Am Meteorol Soc* 79:61–78.