Astronomical metronome of geological consequence

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In PNAS, Kent et al. (1) describe a remarkable geochronologic correlation arising between the continental Triassic–Jurassic Newark Basin strata of eastern North America and the time-equivalent Chinle Formation of western North America that has far-reaching consequences for geology and astronomy, as follows.

A Brief Retrospective

In geology, a reliable "metronome" in the geologic record with a sufficiently short repeat time would greatly enhance the resolving power of the geologic timescale. Astronomers recognized the potential importance of a dominant 405-ky cycle in Earth's orbital eccentricity variation for supplying such a metronome (2, 3), leading geologists to turn to the stratigraphic record of astronomically forced paleoclimate change to search for this cycle. In fact, one of the first geological studies to describe 405-ky scale stratigraphic cycling was on the Triassic–Jurassic Newark Basin lacustrine strata (4, 5) recovered in the National Science Foundation-funded Newark Basin Coring Project, in which each of the prominent 60-m-thick McLaughlin cycles in the cored sequence was assigned a 412.885-ky periodicity based on a now-legacy analytical astronomical solution, BRE74/BER78 (6, 7). Since the 1990s, there have been dozens of reports for strong 405-ky scale cycles in stratigraphic sequences from around the world that appear to bear out this astronomical calculation (8). However, not one of these reports has presented incontrovertible support from independent geochronology that links specific 405-ky cycles, identified by their order of appearance relative to the present day, to those in the astronomical solution. Until now, this has included the Newark Basin, which, besides the flood basalts at the top of the core series, suffers from a lack of datable materials—for example, volcanic ashes—that could help establish a numerical timescale for the core series.

In astronomy, the 405-ky cycle in Earth's orbital eccentricity variation is due to a periodic interaction between the orbital motions of Venus (planet 2) and Jupiter (planet 5), and its influence on Earth's orbit and incoming solar radiation. The periodicity of the interaction is determined by the secular orbital precession frequencies of the two planets, $g_2 - g_5$. This cycle has long been recognized as an important term in Earth's astronomical parameters (9, 10); it is predicted to be very stable, maintaining a constant periodicity over time due to the large mass of Jupiter. The advent of numerical integration reduced the 412.885-ky periodicity of the BRE74/BER78 analytical solution (above) to 404.178 ky in the LAS88/BER90 solution (11–13), then to 406.182 ky (an interim solution by ref. 2), and finally, to 405.091 ky in the LA2004 solution (3). Since 2004, the 405-ky cycle of Earth's orbital eccentricity has remained essentially unchanged for integrations over [+5, −15 My] (negative time is in the past) (14), although its phase drifts slightly in long time integrations, but still less than one full 405-ky cycle by 250 My before present (Ma) (e.g., figure 14 in ref. 14).

The Triassic 405-ky Cycle

Kent et al. (1) demonstrate that assigning a 405-ky periodicity to the McLaughlin cycles is verified by high-precision geochronology. Radioisotopic dates of 209.93 and 210.08 Ma in the Chinle Formation are precisely positioned within the Newark Basin by correlating the reverse polarity magnetozone (PF2r) in which the dates occur to the reverse polarity Chron E16r in the Newark Basin. E16r is dated as 209.95–210.25 Ma by counting the 405-ky McLaughlin cycles from the chron boundaries to the zircon-dated 201.6-Ma Orange Mountain Basalt (OMB) in the upper part of the core series. Thus, PF2r and E16r have indistinguishable ages and affirm the long-suspected 405-ky periodicity of the McLaughlin cycles. Other radioisotope dates in the Chinle Formation at lower (older, 215 Ma) stratigraphic levels provide additional support. Kent et al. (1) also demonstrate that the McLaughlin cycles are phase-locked with the 405-ky orbital eccentricity cycle of the LA2004 astronomical solution for its nominal [+5, −15 My] integration (table 6 in ref. 3) projected back to 215 Ma. The only potential drawback for this remarkable result is that

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the Chinle dates were obtained from detrital zircons in volcaniclastic-rich fluvial sandstone, which raises questions about whether they accurately represent stratigraphic age.

Assuming that the Chinle dates approximate stratigraphic age, the results presented by Kent et al. (1) disentangle multiple issues concerning Triassic chronostratigraphy, the geologic timescale, paleoclimate, evolution, and Solar System behavior, and open new lines of inquiry.

The formula Ecc405:k = 0.216 + (k − 1)*0.405 Ma, which is based on the LA2004 orbital eccentricity solution, is proposed to formalize the 405-ky metronome (15). The constant (0.216), which designates the time between 0 Ma and the peak of the first 405-ky cycle of the full orbital eccentricity solution, may change slightly since the quasi–100-ky variations can mask the precise time of the 405-ky cycle. Application of Ecc405:k to the Newark Basin sequence shows that all 405-ky cycles are accounted for by the McLaughlin cycles from the OMB at 201.6 Ma (Ecc405:498.16) to Chron E16r (Ecc405:518.87 to Ecc405:519.60). Consequently, no time is missing from the upper Newark Series. The metronome also establishes the age of the Carnian/Norian boundary at 227 Ma [compared with 221.0 or 228.4 Ma, options 1 and 2 of *The Geologic Time Scale 2012* (*GTS2012*); ref. 16], the Norian/Rhaetian boundary at 205.5 or 209.5 Ma (compared with 205.4 or 209.5 Ma, options 1 and 2 of *GTS2012*), and the Triassic/Jurassic boundary at 201.4 Ma (compared with 201.3 Ma of *GTS2012*). The metronomic results provide new impetus for documenting all 405-ky cycles in the stratigraphic record (using Ecc405:k) from 0 to 215 Ma at the very least. Most obvious are the McLaughlin cycles of the lower Newark Series, which are the best developed and thoroughly documented (refs. 4, 5, and 17, and many other related papers). The famous cyclic Rhaetian Dachstein Limestone (18, 19) and Carnian–Norian Dolomia Principale (20, 21) European Alps present obvious opportunities for extending the 405-ky metronome between the continental and marine realms of the Late Triassic. Finally, the results of Kent et al. (1) lend support for the expectation of strong 405-ky cycles operating long before 215 Ma, for example, the prominent cyclothems of the Carboniferous Period (359–299 Ma) (22), and beyond.

The Paleoclimatic Response

The McLaughlin cycles as 405-ky orbital eccentricity cycles, and the higher-order cycles within them indicative of quasi–100-ky scale orbital eccentricity and 20-ky scale climatic precession, are all linked to astronomically forced paleoclimate change. McLaughlin cycle boundaries are defined by unusually dark shale beds, which occur approximately once every 60 m along the core series (17). The boundaries are assigned to 405-ky orbital eccentricity maxima, which as noted conforms with the geochronology. Thus, the dark/black beds, representative of deep-lake facies and relatively humid (and warm) climates (23), occurred when orbital eccentricity was high; low orbital eccentricity was associated with shallow-lake and lake-margin facies and relatively arid (and cold) climates. While the Newark Basin sequence formed during a greenhouse climate, icehouse climates responded in kind: When orbital eccentricity was low, climates were cold (and dry), and when high, climates were warm (and humid) (e.g., the Oligocene) (24).

Revisiting Solar System Chaos

Tuning with the 405-ky metronome should resolve other, higher-order cycles related to the quasi–100-ky orbital eccentricity terms. Modulating quasi–100-ky scale cycles are pervasive and prominent in the Newark Basin (5), but they likely do not match any of the theoretical astronomical solutions. This is because the contributing quasi–100-ky terms are thought to be susceptible to disturbance by (unknown) chaotic behavior of the planetary orbits.

Assuming that the Chinle dates approximate stratigraphic age, the results presented by Kent et al. disentangle multiple issues concerning Triassic chronostratigraphy, the geologic timescale, paleoclimate, evolution, and Solar System behavior, and open new lines of inquiry.

However, chaotic behavior in Earth and Mars orbits predicted by LA2004 from 82 to 90 Ma has recently been observed in the quasi–100-ky and obliquity modulations ($g_4 - g_3$ and $s_4 - s_3$, respectively) of cyclic stratigraphy from the Western Interior Seaway, United States (25). In that study, all of the chaotic behavior of Earth and Mars occurred as modulation disturbances in quasi–100-ky terms related to $g_4 - g_5$, $g_4 - g_2$, $g_3 - g_5$, and $g_4 - g_2$ (table 6 of ref. 3), and detected as a $g_4 - g_3$ modulation rapidly transitioning from a 2,400-ky periodicity to a 1,200-ky periodicity, and back (while $s_4 - s_3$ maintained a 1,200-ky periodicity). This harkens to Olsen and Kent (26) who described a persistent 1,750-ky periodicity along the entire Newark Basin core sequence that was interpreted as evidence for a $g_4 - g_3$ term (i.e., 2,400 ky shortened to 1,750 ky) of the orbital eccentricity, and it is worth further probing Solar System dynamics to explain this behavior. The absence of an obliquity cycle in the Newark Basin strata (to measure $s_4 - s_3$) necessitates seeking another coeval astronomical record, with one excellent candidate section emerging in northwest China (27).

Confidence in Astrochronology

The independent confirmation of the 405-ky orbital eccentricity cycle in these ancient sedimentary deposits has been long-sought and will be enthusiastically welcomed by geologists. It represents an important "benchmark" in the rapidly expanding annals of cyclostratigraphy, the branch of stratigraphy dedicated to the study of astronomically forced climate change and the development of an astrochronology to support and refine the geologic timescale.

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