Creation Research Society Quarterly 2016. 53:103–109.

Cyclostratigraphy

Part II: History of the Method

John K. Reed and Michael J. Oard*

Abstract

Part I of this series described the modern stratigraphic method of cyclostratigraphy, which is linked to astrochronology. The latter uses properties of Earth's orbital mechanics to develop an absolute chronometer back through time. Cyclostratigraphy uses properties of sedimentary rocks as proxies for these orbital cycles to connect the astronomical "clock" to the sedimentary record. In this part of the series, we trace the historical development of these methods, their increasing influence on the geologic timescale, and the implications for a more gradualistic view of uniformitarianism.

Introduction

Creationists must remain current with trends in the earth sciences, especially those that support secular natural history. Stratigraphy is one of these; it is at the center of Earth's history and has evolved over the last half century from a simpler, more empirical discipline to a complex, integrated one, centered on the geological timescale. Changes in stratigraphy are mirrored by those in the timescale. Its current incarnation is of nearly one hundred Phanerozoic stages of a few million years duration, which are defined by the fiat placements of GSSPs (Reed, 2008). Increasing detail requires increasing precision in geochronology, which has spurred a demand for new methods. Cyclostratigraphy has moved rapidly to a place of prominence for Cenozoic rocks because of its alleged precision of 10^4–10^5 years (e.g., 0.02 million years; Hinnov and Ogg, 2007), and geologists are hopeful that it can be extended to older rocks as the method develops.

Cyclostratigraphy uses features of sediments and sedimentary rocks as proxies for changes in climate. These proxies are thought to mirror changes in solar insolation driven by cyclical changes in eccentricity, precession, and obliquity over time (Reed and Oard, 2015). Popular proxies include oxygen and carbon isotope ratios, clay and microfossil assemblages, lithology changes in lithofacies, grain size, and sediment color. Some of these are also used to date ice cores to date glacial and interglacial periods, especially those of the Pleistocene (Hebert, 2014; Oard, 2005).

Many creationists, like many other nonspecialists, are unaware of the dramatic advances in stratigraphy and corresponding changes in the timescale. Since methods in natural history are commonly driven by human factors, it is important to trace these factors, as well as the technology, that have contributed to the development of cyclostratigraphy. In this paper, we will trace these developments, first in the area of astrochronology—an outgrowth of the Milankovitch theory of the ice ages—and then in stratigraphy itself. This bipartite division will pave the way for the final two

---

* John K. Reed, Ph.D., Birmingham, AL reed4004@gmail.com
Michael J. Oard, M.S., Bozeman, Montana
Accepted for publication December 5, 2016

papers in this series, which will critique astrochronology and cyclostratigraphy.

The Astronomical Theory of Ice Ages

Astrochronology grew out of the theory that ice ages occurred due to cyclical changes in orbital mechanics. The early emphasis on ice ages reflected the popularity of that topic in the late nineteenth and early twentieth centuries. Miall agreed with Zeller (1964) and Dott (1992) that geologists had a propensity for cyclic explanation, noting, "Two themes that recur throughout the evolution of geological thought are *pattern recognition* and *cyclicity*" (Miall, 2010, p. 26). There is nothing inherently wrong with these themes, although Zeller's (1964) study demonstrated that geologists often see pattern where none exists.

Cyclostratigraphy, described in Reed and Oard (2015), attributes cyclical changes in glacial and interglacial periods to cycles in: (1) Earth's eccentricity, with strong maximum variations at approximately 100,000 and 400,000 years; (2) the precession of the equinoxes, with a major periodicity of 22,000 years; and (3) the tilt of Earth's rotational axis, with a period of 41,000 years. Other peaks are recognized, but these are considered the primary factors affecting sunlight, or *insolation*, between latitudes and seasons. In theory, changes in summer insolation at high latitudes affect glacial/interglacial oscillations. Less summer sunlight results in glacial episodes, while the opposite brings interglacial periods.

The astronomical theory was originally developed hand in hand with the four-ice-age model. But during the 1960s and 1970s, scientists realized that there had been dozens of these oscillations in the Northern Hemisphere and inferred that there had been dozens of ice ages. Today, based on cycles in deep-sea sediment cores, scientists believe that there were about fifty ice ages during the last 2.6 million years—the Pleistocene or the Quaternary of the geological timescale (Pillans and Gibbard, 2012).

Early Ideas

The idea of cycles in earth processes found its way into geology from its inception (Dott, 1992; Gould, 1987). Cyclothems and other sedimentary indications of depositional cycles were popular throughout the twentieth century; Barrell (1917) spoke of the role of Earth's "rhythms" in geology. The idea of astronomical climate forcing was proposed even earlier, by Herschel (1830), and developed by mathematician Joseph Adhémar (1842) in his book *Revolutions of the Sea*. Newspaper publisher Charles MacLaren linked glaciation to sea-level change in 1842 (Miall, 2010).

Seizing on Kepler's theory of elliptical orbits, Adhémar suggested that the differences in sunlight, caused by the difference between *aphelion*, Earth's greatest distance from the sun (94.5 million miles) on its elliptical path, and *perihelion*, its nearest approach (91.5 million miles), affected climate and contributed to the ice ages. He reasoned that elliptical variations, combined with the precession of the equinoxes caused ice ages to cycle every 22,000 years but alternate between the hemispheres every 11,000 years. He claimed that the Southern Hemisphere was already in an ice age, as evidenced by the Antarctic ice sheet, because the planet was at aphelion during the Southern Hemisphere winter, resulting in seven less days of sunlight.

Adhémar was correct that Earth's eccentricity varies slightly, from near zero (zero being a perfect circle and one a straight line) to 0.06 in a 100,000-year cycle. Thinking that the eccentricity influenced climate, which varied between hemispheres, Adhémar suggested that the most recent ice age in the Northern Hemisphere occurred 11,000 years ago and that another would begin in another 11,000 years. His theory was initially rejected because scientists of his day did not believe that slight changes in sunlight caused by eccentricity were a sufficient cause of the ice ages.

In the 1860s and 1870s, James Croll, a self-taught Scottish scientist, resurrected Adhémar's idea. While affirming the importance of eccentricity, he focused on changes in Earth's tilt, noting that eccentricity modulates the amplitude of the precession cycle. When eccentricity is high, precession is too. When eccentricity is low, precession is low. French mathematician Le Verrier had previously shown that the total amount of sunlight on Earth during an entire year is unaffected by eccentricity, but Croll believed that when the two cycles were high, climate could change enough to start an ice age due to less winter sunlight. But the effect of both cycles was still small, so Croll added a boosting mechanism of positive feedback. Slight decreases in winter temperatures led to more snow cover, which in turn reflected more sunlight, boosting the cooling. Combining these factors, Croll predicted that the most recent glacial epoch had occurred between 80,000 and 250,000 years ago and that ice ages oscillated between the hemispheres, out of phase, every 11,000 years, in tune with the precession cycle.

Croll's ideas generated intense debate. Seeds and plants found between layers of glacial deposits in the Alps reinforced the idea of multiple ice ages. Scientists posited between two and six ice ages but challenged Croll's timing. Instead of 80,000 years ago, they insisted the most recent ice age ended only 10,000 years ago and that glaciation did not cycle between the hemispheres. They cited the ongoing migration of Niagara and St Anthony's falls in the north-central United States as evidence of a recent ice age. Both had been receding, they thought, since the end of the last ice age, and they used the rate of recession to date that event between 6,000 and 32,000 years. The more recent date was based on a more rapid recession of Niagara Falls and was based on careful observations, but the older date was more generally accepted because it was proposed by Lyell.

Croll's theory was first rejected by American scientists and then later in Europe as, once more, meteorologists claimed the orbital effects were too minor to trigger ice ages:

> Moreover, theoretical arguments were advanced against the theory by meteorologists who calculated that the variations in solar heating described by Croll were too small to have any noticeable effect on climate. (Imbrie and Imbrie, 1979, p. 96)

So, the astronomical theory lay dormant—just one more fading theory of the ice ages.

Milankovitch Rescues the Astronomical Theory

Geology entered another cycle of theorizing about astronomically caused climate change when Milutin Milankovitch, an engineer from Serbia, became interested in the ice ages. With help from renowned climatologist, Wladimir Köppen, he proposed that ice ages were triggered by cool summers, not cold winters, as Adhémar and Croll had believed. Hot summers melted snow, he reasoned, even after cold winters. Cooler summers would preserve snow cover, which would then accumulate to form glaciers and ice sheets. In 1924, Köppen and Wegener used the calculations of Milankovitch to correlate alpine ice-age deposits with insolation minima. Others noticed an apparent agreement between Milankovitch's solar radiation curves and the timing of the four ice ages (Penck and Brückner, 1909) on the north slopes of the Alps. This "confirmation" was so close that even the "great interglacial" between the second and third ice ages could be seen on the Milankovitch curves. This "great interglacial" was deduced from the thickness of Swiss lacustrine sediments. It was a striking "verification" that persuaded a majority of scientists that there was an astronomical trigger for the ice ages. Milankovitch (1941) published what most consider the landmark research for the astronomical theory, and scientists began using his curves to "date" surficial glacial debris. Schaefer (1953) had earlier called the Alpine theory into question with the discovery of warm-climate mollusks in terraces supposedly formed during glacial melting, but his results were ignored.

But this simple scheme faced problems. Geologists soon realized that each ice age would erode sediments deposited by previous ice ages and redeposit them. The apparent succession of tills for the four ice ages in the northern Midwest of the United States was discontinuous and jumbled, making it hard to test Milankovitch's theory in the field. A potential solution came when Libby introduced carbon-14 dating. Scientists used it to date ice-age deposits, but the carbon dates did not match Milankovitch's curves. They found an interglacial warm phase during a summer insolation minimum at 65°N, and glaciation during a winter insolation maximum. These contradicted the theory, and during the 1950s and early 1960s, the Milankovitch mechanism appeared dead:

> By 1969 it was embarrassingly clear that the entire climatic scheme developed for the Alpine terraces by Penck and Brückner, expanded by Eberl, and accepted by a generation of geologists was no more than a house built—not on sand—but on shifting gravel. And when the house finally collapsed, the argument used by Köppen and Wegener to confirm the Milankovitch theory collapsed with it. (Imbrie and Imbrie, 1979, p. 156)

Marine Geology Revives the Astronomical Theory

But the theory was revived to explain the explosion of data from the new discipline of marine geology. After World War II, mapping and sampling the ocean floor was pursued with great energy. In 1968, the Deep Sea Drilling Program (DSDP) began under the auspices of JOIDES, with exploration legs aboard the *Glomar Challenger*. In 1975, the International Phase of Ocean Drilling united scientists from the United States, the UK, France, West Germany, Japan, and Russia. In 1985, the DSDP was replaced by the Ocean Drilling Program (ODP) with the new research vessel, *JOIDES Resolution*. In 2003, the ODP was replaced by the International Ocean Discovery Program (IODP). As of 2015, 356 legs had been completed, and the vast data from the world's oceans has revolutionized earth science (IODP, 2015).

One of the primary sources of data from ocean drilling was a set of cores of ocean-floor sediment. Initially, it was hoped that sea-floor sediments would show a pristine record of each ice age. Scientists only needed to identify the proper sedimentary proxy to identify glacial and interglacial periods. Researchers proposed several. One was the percentage of $CaCO_3$ in each layer, based on the assumption that the volume of $CaCO_3$ would be controlled by temperature. As a result, they correlated percent $CaCO_3$ to glacial and interglacial periods, and the numerous cycles suggested numerous ice ages. But other methods were being developed.

Another potential proxy was the abundance of the foraminifera, *Globorotalia medardii*. Foraminifera are microscopic shells built by plankton. Scientists immediately noticed that higher occurrences of these foraminifera corresponded to the long interglacial proposed by Penck and Brückner (1909). Another proxy was being developed by Emiliani (1955, 1966), who proposed the use of oxygen isotope fractions in calcareous foraminifera shells, thinking that changes in oxygen isotope ratios could be correlated to ocean temperature and salinity, which would change slightly during glacial and interglacial periods. The isotope ^{17}O is rare, but the ratio of ^{16}O to ^{18}O offered hope as a reliable proxy. Emiliani (1966) discovered that the pattern of ice ages based on this ratio differed from that using the foraminifera curve, but he was able to convince scientists that the oxygen isotope ratios reflected astronomically driven climate change.

Problems with Emiliani's solution soon appeared; for example, he thought that the glacial/interglacial cycle was on the order of 40,000 to 50,000 years (Emiliani, 1955). But geologists considered the oxygen isotope method superior to that comparing the relative abundances of warm and temperate species of pelagic foraminifera or carbonate percentages. Kemp and Eger (1967) noted that it was already then the preferred method by geologists. Shackleton (1967) proposed that the oxygen isotope ratios could be used if they were seen as reflecting ocean volume, rather than directly showing changes in temperature and salinity. This would indicate changes in sea level that could then be correlated to glacial and interglacial periods. This is due to the smaller mass of the water molecule with ^{16}O than a water molecule made with ^{18}O. The lighter water molecule made with ^{16}O would more likely evaporate and fall as precipitation on the continent. This would tie up water molecules high in ^{16}O in ice sheets. leaving behind in the oceans water molecules high in ^{18}O.

Work continued and in what is considered the definitive beginning of widespread acceptance of the "Milankovitch processes" (Miall, 2010, p. 327), Hays et al. (1976) were able to show a quantitative link between oxygen isotope ratios and Milankovitch cycles. Then Imbrie et al. (1984) showed that the isotope signature could be correlated to the Brunhes magnetic chron in all the oceans, indicating its global value. Imbrie (1985) followed up with an astronomical theory linking orbital mechanics to the Pleistocene ice ages.

Paralleling these advances in isotope profiling of cores was the development and expansion of the magnetostratigraphic timescale, which for several decades was used to identify sea-floor spreading rates (Vine and Matthews, 1963). The two methods began to be used in tandem, and still are (Kodama and Hinnov, 2015), but this has raised several questions. Among them was an indication that ice ages were most strongly influenced by the 100,000-year eccentricity cycle, which has a minimal effect on insolation.

The astronomical theory was originally developed to model the antiquated four-ice-age model. As the number of ice ages grew, the astronomical clock was adjusted to accommodate them. Today, based on cycles in deep-sea sediment cores, scientists believe that there were approximately fifty ice ages during the Pleistocene (Quaternary) (Pillans and Gibbard, 2012).

Pushing Deeper into the Past

If orbital forcing of climatically controlled sedimentation during the Pleistocene ice ages could be seen in marine sediment cores, geologists reasoned that climate forcing might extend to other depositional environments and be a major factor in deposition through time. The basis for the idea was firmly in place, thanks to a body of work on North American cyclothems (Merriam, 1964; Wanless and Weller, 1932) and speculation by G. K. Gilbert (1895) that orbital cycles influenced carbonate content in Cretaceous strata in Colorado. As the theory took hold, climate-based cyclicity was identified at other locations (e.g., Fischer, 1986; Van Houton, 1964). Milankovitch and the DSDP efforts focused attention on the Pleistocene ice ages, as noted above, but the idea of climate forcing in older sediments required merely a shift in focus; the paradigm had already been established. As Miall (2013, p. 176) noted:

> A key question, central to the issue of sedimentation rate and time scales, is the degree to which orbital frequencies could be retrodicted or reconstructed for the distant geological past, given the possibility of changes in the orbital behavior of Earth.

As geologists began seeking examples of climate forcing in older sediments, they faced a problem of circularity: "some astronomers … suggesting that geological data could be used to calibrate the orbital frequencies of the geological past" (Miall, 2013, p. 176), while "geologists experienced in the incompleteness and inconsistencies of field data and knowledgeable about the warnings associated with the use of time series analysis offered by signal theorists" (Miall, 2013, p. 176) understood the necessity of a standard *for* the stratigraphic record, not vice versa. Another problem was the ability to calibrate the relatively precise astronomical curves to accepted dates, since radiometric methods cannot reliably achieve the precision of tens to hundreds of thousands of years.

Another problem—though one not fully appreciated even today—was the completeness of the sedimentary record. After all, if hundreds of thousands of years of section were missing in a given outcrop, each hiatus would have to be identified and dated before the resulting astronomical spectral peaks could be properly interpreted. Practically speaking, the latter two problems required that astrochronology be able to justify its timescale apart from the sedimentary record, if it was to be used as a stratigraphic dating and correlation method. But this has proven difficult because the two are so intertwined. Miall (2013, p. 171) noted that astrochronology was a "logical extension of cyclostratigraphy," acting as "a 'pacemaker' tracing Earth history."

Despite these problems, geologists quickly began to interpret increasingly older sediments as the products of astronomical climate forcing, based on extrapolation of sea-level changes estimated from Pleistocene ice ages. Once Imbrie (1985) had proposed a complete cyclostratigraphic timescale for the Pleistocene, geologists moved to older sediments. Shackleton et al. (1990) began to push the clock back, but it was the landmark work of Hilgen (1991a, 1991b) on pelagic sediments on the coast of Sicily that broke away from the limits of the Pleistocene and showed how to migrate the astronomical clock back into the Cenozoic. Hinnov (2004), in an article supporting the application of cyclostratigraphy to the Geological Time Scale 2004 (GTS2004), extended this timescale back to 23 Ma, in the mid-Tertiary. In conjunction, mathematical development of the Astronomical Time Scale (ATS) improved, indicating that cyclostratigraphic calibration and correlation was possible for older sediments.

In addition, Hinnov (2004) and others distinguished between a cyclostratigraphic timescale linked back through time and tied firmly to accepted dates, and less precise "floating timescales" based on the 405-kyr eccentricity signal. These "floating timescales" were an initial step and would become a part of the calibrated record as ties were established to the timescale stages. "Floating scales" are calibrated to specific sections of the stratigraphic record but not fully linked from present to past. Since accepted dates for key boundaries of the timescale are tied to radiometric methods, it is difficult to demonstrate a complete astronomical record. For example, if a radiometric date had an error range of one million years, that would be 2.5 times the length of an eccentricity cycle and 50 times the length of a precession cycle. Interpretation is required; Hinnov and Ogg (2007) claimed that the beginning of the Messinian salinity event corresponded to climate forcing by an eccentricity cycle. They provide a good summary of progress through the early twenty-first century, confidently asserting that the ATS would be soon fully calibrated all the way to the base of the Mesozoic.

Various methods have been developed over recent decades to connect the astronomical and stratigraphic signals. Hinnov and Ogg (2007, p. 242) noted, "Astronomical (orbital) tuning is the mainstay of ATS calibration." Astronomical tuning involves the statistical time-series analysis of spectral peaks that can then be linked to the various astronomical cycles. However, Miall (2015) warns of pitfalls in this method when it is not linked to a careful sedimentological/facies analysis. Nevertheless, extraordinarily rapid progress is being made.

> Cyclostratigraphic studies have been published or are in progress for at least one section spanning each geologic stage throughout the Cenozoic and Mesozoic, and there is a steadily growing literature devoted to Paleozoic cyclostratigraphy. (Hinnov and Ogg, 2007, p. 242)

Furthermore, geologists are using cyclostratigraphy to calibrate a chronology that sheds light on everything from the motions of the planets to evolution. It is clearly a time of great optimism that cyclostratigraphy will unlock many mysteries of the past. Voices of caution exist however. Miall (2015, p. 29) stated:

> It is common practice to show the sections in the time domain, which makes correlation to a calculated

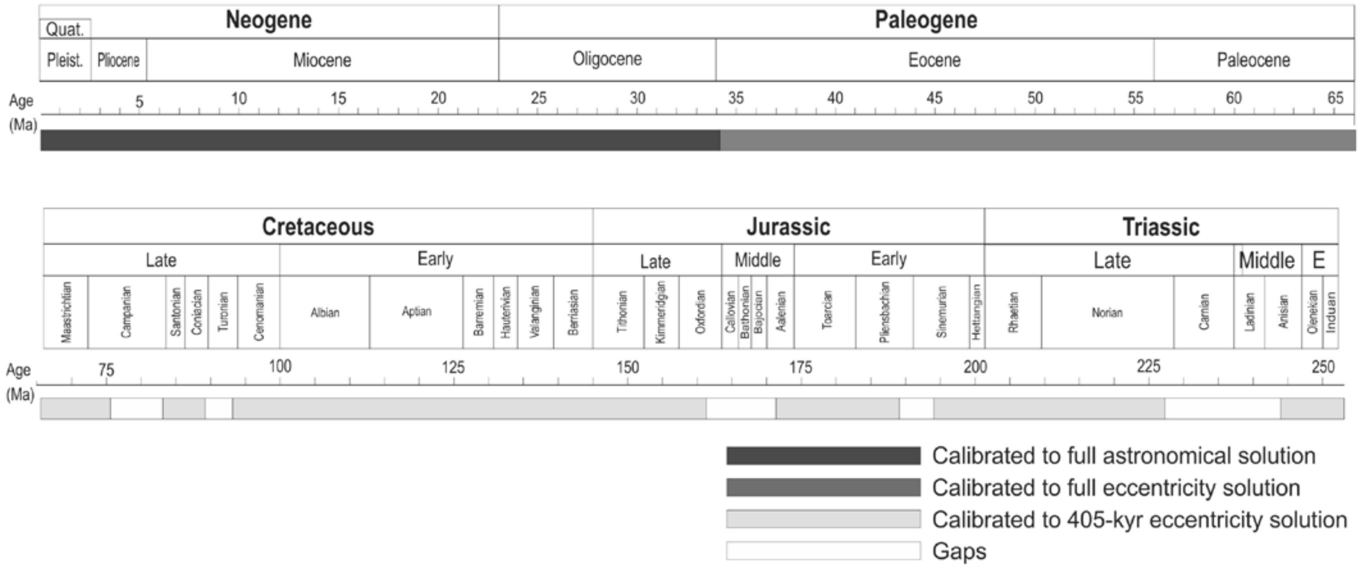

Figure 1. Parts of geological timescale calibrated to astronomical timescale as of 2012. After Hinnov and Hilgen (2012).

> astronchronological scale straightforward. However, caution is to be recommended, because this practice may hide irregularities in the succession caused, for example, by autogenic processes. Time series analysis of sections in the thickness domain cannot be used to explore orbital control where there are significant autogenic effects on lithofacies and unit thickness. … it is incumbent on proponents of cyclostratigraphic control for hanging sections representing the distant geological past to do more than provide statistical "proof" of their reality, such as from amplitude spectra of time series studies.

At present, mathematical models of Earth's orbital dynamics through time have been developed to produce astronomical Milankovitch curves back through the Cenozoic. Significant recent advances in mathematical models of orbital mechanics through time (Laskar et al., 2004; Laskar et al., 2011) extend a full astronomical solution, or a composite continuous cyclostratigraphic correlation, back to 34 Ma (Figure 1). It provides a full eccentricity solution to the base of the Cenozoic (66 Ma) and a partial solution based on the 405-kyr eccentricity cycle to the base of the Mesozoic (250 Ma) (Hinnov and Hilgen, 2012). This has been an amazing progression in less than two decades.

Conclusion

Recent decades have seen explosive activity bent on finding an "astronomical clock" in sediments throughout deep time. Patches of Mesozoic strata from the Triassic, Jurassic, and Cretaceous have all been calibrated to the astronomical clock, although geologists have not yet been able to link these sections to cover the entire Mesozoic (see chapters 25–27 of Gradstein et al., 2012). Other geologists are "seeing" astronchronological cycles in Paleozoic sediments such as the Permian Castile Formation (Anderson, 2011), Pennsylvanian cyclothems (Heckel, 2008), and Mississippian limestones in Ireland (Schwarzacher, 1993). Hinnov and Hilgen (2012) report "astronomical-scale cycles" in Devonian, Silurian, Ordovician, and Cambro-Ordovician sediments. Some work has even been started in Precambrian sediments as old as the Archean (Hofmann et al., 2004).

References

Adhémar, J. 1842. *Les Révolutions de la Mer, Déluges Périodiques*. Carilian Gourey et V. Dalmort, Paris, France.

Anderson, R.Y. 2011. Enhanced climate variability in the tropics: a 200,000 yr annual record of monsoon variability from Pangea's equator. *Climate of the Past* 7:757–770.

Barrell, J. 1917. Rhythms and the measurement of geologic time. *Geological Society of America Bulletin* 28:745–904.

Croll, J. 1875. *Climate and Time in their Geological Relations*. Appleton, New York, NY.

Davis, O.K. 1984. Multiple thermal maxima during the Holocene. *Science* 225:617–618.

Dott, R.H., Jr. (editor). 1992. *Eustasy: The Ups and Downs of a Major Geological Concept*. Geological Society of America Memoir 180, Boulder, CO.

Emiliani, C. 1955. Pleistocene temperatures. *Journal of Geology* 63:538–578.

Emiliani, C. 1966. Isotopic paleotemperatures. *Science* 154:851–857.

Fischer, A.G. 1986. Climate rhythms recorded in strata. *Annual Review of Earth and Planetary Sciences* 14:351–376.

Gilbert, G.K. 1895. Sedimentary measurement of geologic time. *Journal of Geology* 3:121–127.

Gould, S.J. 1987. *Time's Arrow, Time's Cycle: Myth and Metaphor in the Discovery of Geological Time*. Harvard University Press, Cambridge, MA.

Gradstein, F.M., J.G. Ogg, and A.G. Smith (editors). 2004. *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, UK.

Gradstein, F.M., J.G. Ogg, M. Schmitz, and G Ogg (editors). 2012. *The Geologic Time Scale 2012*. Elsevier, New York, NY.

Hays, J.D., J. Imbrie, and N.J. Shackleton. 1976. Variations in the earth's orbit: pacemaker of the ice ages. *Science* 194:1,121–1,132.

Hebert, J. 2014. Circular reasoning in the dating of deep seafloor sediments and ice cores: the orbital tuning method. *Answers Research Journal* 7: 297–309.

Heckel, P.H. 2008. Pennsylvanian cyclothems in mid-continent North America as far field effects of waxing and waning Gondwana ice sheets. In Fielding, C.R., T.D. Frank, and J.L. Isbell (editors), *Resolving the Late Paleozoic Ice Age in Time and Space*, pp. 275–289, Geological Society of America Special Paper 441, Boulder, CO.

Herschel, J.F.W. 1830. On the geological causes which may influence geological phenomena. *Geological Transactions* 3:293–299.

Hilgen, F.J. 1991a. Extension of the astronomically calibrated (polarity) time scale to the Miocene-Pliocene boundary. *Earth and Planetary Science Letters* 107:349–368.

Hilgen, F.J. 1991b. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. *Earth and Planetary Science Letters* 104:226–244.

Hilgen, F.J., K. Kuiper, W. Krijgsman, E. Snel, and E. van der Laan. 2007. Astronomical tuning as the basis for high resolution chronostratigraphy: the intricate history of the Messinian Salinity Crisis. *Stratigraphy* 4:231–238.

Hinnov. L.A. 2004. Earth's orbital parameters and cycle stratigraphy. In Gradstein, F.M., J.G. Ogg, and A.G. Smith (editors), *A Geologic Time Scale 2004*, pp. 55–62. Cambridge University Press, Cambridge, UK.

Hinnov, L.A, and F.J. Hilgen. 2012. Cyclostratigraphy and astrochronology.

In Gradstein, F.M., J.G. Ogg, M.D. Schmitz, and G.M. Ogg (editors). *The Geologic Time Scale 2012*, pp. 63–84. Elsevier, Amsterdam, Netherlands.

Hinnov, L.A., and J.G. Ogg. 2007. Cyclostratigraphy and the astronomical time scale. *Stratigraphy* 4:239–251.

Hofmann, A., P.H.G.M. Dirks, and H.A. Jelsma. 2004. Shallowing upward carbonate cycles in the Belingwe Greenstone Belt, Zimbabwe: a record of Archean sea level oscillations. *Journal of Sedimentary Research* 74:64–81.

Imbrie, J. 1985. A theoretical framework for the Pleistocene ice age. *Journal of the Geological Society, London* 142:417–432.

Imbrie, J., J.D. Hays, D.G. Martinson, et al. 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine 18O record. In Berger, A.I., J. Imbrie, J.D. Hays, G. Kukla, and B. Saltzman (editors), *Milankovitch and Climate*, Part I. D. Riedel, Dordrecht, Netherlands.

Imbrie, J., and K.P. Imbrie. 1979. *Ice Ages: Solving the Mystery*. Enslow Publishers, Short Hills, NJ.

IODP.org. International Ocean Discovery Program. http://www.iodp.org (October, 2015).

Kemp, W.C., and D.T. Eger. 1967. The relationships among sequences with applications to geological data. *Journal of Geophysical Research* 72:743.

Kodama, K.P., and L.A. Hinnov. 2015. *Rock Magnetic Cyclostratigraphy*. John Wiley & Sons, Chichester, UK.

Laskar, J., A. Fienga, M. Gastineau, and H. Manche. 2011. La2010: a new orbital solution for the long-term motion of the Earth. *Astronomy and Astrophysics* 532 (A89): 1–15. www.imcce.fr/Equipes/ASD/insola/earth/earth.html *(accessed November, 2015)*.

Laskar, J., P. Robutel, J. Joutel, M. Gastineau, A.C.M. Correia, and B. Levrard. 2004. A numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics* 428:261–285.

Merriam, D.F. (editor). 1964. *Symposium on Cyclic Sedimentation*. Kansas Geological Survey Bulletin 169. Lawrence, KS.

Miall, A.D., 2010, *The Geology of Stratigraphic Sequences*, second edition. Springer, New York, NY.

Miall, A.D. 2013. Sophisticated stratigraphy. In Bickford, M.E. (editor), *The Web of Geological Sciences: Advances, Impacts, and Interaction*, pp. 169–190. Geological Society of America Special Paper 500, Boulder, CO.

Miall, A.D. 2015. Updating uniformitarianism: stratigraphy as just a set of 'frozen accidents.' In Smith, D.G., R.J. Bailey, P.M. Burgess, and A.J. Fraser (editors), *Strata and Time: Probing the Gaps in our Understanding*, pp. 11–36. Geological Society, London Special Publication 404, London, UK.

Milankovitch, M. 1941. *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem*. Royal Serbian Academy, Section of Mathematical and Natural Sciences, Belgrade, Yugoslavia. Reissued in English in 1998 as *Canon of Insolation and the Ice-Age Problem*. Serbian Academy of Sciences and Arts, Section of Mathematical and Natural Sciences, Belgrade, Yugoslavia.

Oard, M.J., 1984a. Ice ages: the mystery solved? Part I: the inadequacy of a uniformitarian ice age. *Creation Research Society Quarterly* 21:66–76.

Oard, M.J., 1984b. Ice ages: the mystery solved? Part II: the manipulation of deep-sea cores. *Creation Research Society Quarterly* 21:125–137.

Oard, M.J., 1985. Ice ages: the mystery solved? Part III: paleomagnetic stratigraphy and data manipulation. *Creation Research Society Quarterly* 21:170–181.

Oard, M.J., 1997. *Ancient Ice Ages or Gigantic Submarine Landslides?* Creation Research Society Books, Chino Valley, AZ.

Oard, M.J., 2005. *The Frozen Record: Examining the Ice Core History of the Greenland and Antarctic Ice Sheets*. Institute for Creation Research, Dallas, TX.

Oard, M.J., 2013. The reinforcement syndrome ubiquitous in the earth sciences. *Journal of Creation* 27(3): 13–16.

Penck, A., and E. Brückner. 1909. Die Alpen im Eiszeitalter. Tauchnitz, Leipzig, Germany.

Pillans, B., and P. Gibbard. 2012. The Quaternary Period. In Gradstein, F.M., J.G. Ogg, M. Schmitz, and G. Ogg (editors), *The Geologic Time Scale 2012*, pp. 979–1,010. Elsevier, New York, NY.

Reed, J.K. 2008. Toppling the timescale, part IV: assaying the golden (FeS_2) spikes. *Creation Research Society Quarterly* 45:81–89.

Reed, J.K., and M.J. Oard. 2015. Cyclostratigraphy. part I: what is cyclostratigraphy? *Creation Research Society Quarterly* 52:95–105.

Schaefer, I. 1953. Die donaueiszeitlichen Ablagerungen an Lech und Wertach. *Geologia Bavarica* 19:13–64.

Schwarzacher, W. 1993. Cyclostratigraphy and the Milankovitch theory. *Developments in Sedimentology* 54:225.

Shackleton, N. 1967. Oxygen isotope analyses and Pleistocene re-assessed. *Nature* 215:15–17.

Shackleton, N.J., A. Berger, and W.A. Peltier. 1990. An alternative astronomical calibration of the lower Pleistocene time scale based on ODP Site 677. *Transactions of the Royal Society of Edinburgh, Earth Sciences* 81:251–261.

Van Houton, F.B. 1964. Cyclic lacustrine sedimentation, Upper Triassic Lockatong formation, central New Jersey and adjacent Pennsylvania. In Merriam, D.F. (editor), *Symposium on Cyclic Sedimentation*, pp. 495–531. Kansas Geological Survey Bulletin 169. Lawrence, KS.

Vine, F.J., and D.H. Matthews. 1963. Magnetic anomalies over oceanic ridges. *Nature* 199:947–949.

Wanless, H.R., and J.M Weller. 1932. Correlation and extent of Pennsylvanian cyclothems. *Geological Society of America Bulletin* 43:1003–1016.

Zeller, E.J. 1964. Cycles and psychology. *Kansas Geological Survey Bulletin* 169:631–636. http://www.kgs.ku.edu/Publications/Bulletins/169/Zeller/index.html.