Creation Research Society Quarterly 2015. 52:95–105.

Cyclostratigraphy

Part I: What Is Cyclostratigraphy?

John K. Reed and Michael J. Oard*

Abstract

Stratigraphy has undergone dramatic changes. From a simple timescale resting on paleontology and relatively few and less precise radiometric dates, it has become an integrated, sophisticated discipline built around a timescale that is increasingly complex and supported by new and equally complex methods. Creationists must understand and address these changes, especially those changes in the methods. This series will focus on one of the newer methods: cyclostratigraphy and its associated astrochronology. Cyclostratigraphy links various properties of sedimentary rocks to an astronomical "clock" based on the extrapolation of orbital mechanics into the past. This clock sends a signal of varying sunlight to Earth, manifested as "Milankovitch cycles," that are thought to force climate change sufficient to be recorded in sedimentary rocks.

Introduction

Torrens (2002, p. 251) stated: "The science of geology is all about time." He said that stratigraphy is "the only area of geology that is truly unique, other branches of geology are too often borrowed bits of physics, chemistry, or biology." But secular geology as a historical discipline rejects biblical history, and through its aura of "science" has led many Christians to accept deep time. Creationist pioneers knew they needed to address deep time as well as evolution, which meant discrediting, at a minimum, the geochronologic timescale and its supporting methods. In the 1960s and 1970s, these were predominantly evolutionary biostratigraphy and radiometric dating. Gish (1972) noted weaknesses in biostratigraphy—field exceptions that included "living fossils," the imprecise ranges of many taxa, and circular reasoning. Others began to address problems with isotopic techniques (Gentry, 1966; Whitelaw, 1968, 1970; Woodmorappe, 1979).

Creationism became a robust scientific Christian response to secular geology not seen since the nineteenth-century scriptural geologists (Mortenson, 2004). This coincided with a revolution in geologic thought driven by an explosion in the exploration of the deep oceans, the ongoing search for oil and gas, and new theoretical ideas, like plate tectonics and neocatastrophism. These also drove major changes in stratigraphy, ongoing since the latter twentieth century. Plate tectonics affected views of sedimentary basins, large-scale depositional processes, marine geology, and tectonics. Neocatastrophism grew out of theoretical (e.g., Hooykaas, 1963) and empirical (Ager, 1973, 1993; Alvarez et al., 1980; Bretz, 1923, 1925) challenges to uniformitarianism. However, the essential commitment to Lyellianism remains dominant in historical science (Kravitz, 2013; Miall, 2012; Reed, 2010, 2011;

---

* John K. Reed, Ph.D., Birmingham, AL reed4004@gmail.com
Michael J. Oard, M.S., Bozeman, Montana
Accepted for publication August 28, 2015

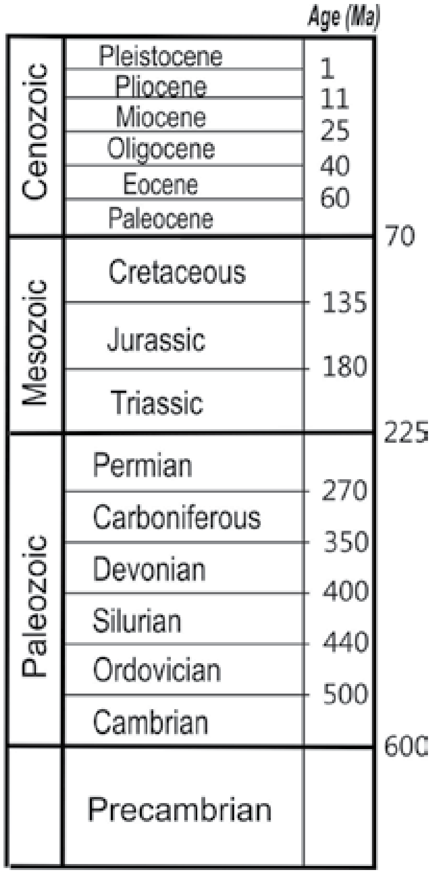


Figure 1. Geologic timescale from Holmes (1960).

Reed and Williams, 2012; Romano, 2015). Geologists also are beginning to examine some of their assumptions and to recognize the tension between inductive (using specific examples to reach general conclusions) and deductive (reasoning from general principles to specifics) approaches to stratigraphy (Cleland, 2013; Miall, 2004).

Stratigraphy has been profoundly affected. We suspect that many remain unaware of the extent, centered on an increasingly complex and refined geologic timescale compared to that of the mid-twentieth century (Figure 1). The International Commission on Stratigraphy (ICS) has taken the lead as the caretaker of the timescale (Gradstein et al., 2004a, 2012). Comparison of the timescale from 1960 to today (Figure 2) shows a dramatic increase in detail.

> Its supporting methods have also grown more complex, though the purpose remains the same: It is, in fact, fundamental to the understanding of the history of Earth that events be meticulously correlated in time. (Miall, 2004, p. 11)

Traditional methods (biostratigraphy and radiometric dating) have become more sophisticated. The ability to store, share, and analyze large databases has combined with statistical and mathematical models to extract more information from fossil assemblages. Technological innovations in sampling, laboratory methods, and analysis also have led to new and improved isotope methods (Gradstein et al., 2012). Second, new methods have been introduced and used with increasing confidence. Two "newcomers" are *magnetostratigraphy* and *cyclostratigraphy*, with stable isotope stratigraphy and sequence stratigraphy also becoming prominent. At present, the basic pillars of the timescale include: (1) biostratigraphy, (2) isotopic dating, (3) magnetostratigraphy, and (4) cyclostratigraphy (Figure 3).

Through all these changes, the goal of stratigraphy remains the same. It is to classify scattered rock formations by assigning them an age and then globally correlating the rocks by those ages. Historically, this has been done in a two-step process: (1) chronostratigraphy and (2) geochronology. *Chronostratigraphy* is the ordering of rocks into a relative sequence, and *geochronology* assigns them an absolute age (Ferrusquía-Villafranca et al., 2009). Combining the two methods yields the timescale shown in Figure 2. However, a new school of thought is attempting to subsume chronostratigraphy into geochronology:

> We consider that the practice of Chronostratigraphy today defines the time framework of Geochronology, because intervals of geological time are now being precisely defined within rock successions by GSSPs. *The effect of this is that Chronostratigraphy and Geochronology should become one and the same discipline*. (Gradstein et al., 2004b, p. 41, emphasis added)

This new approach restricts empirical uncertainty but at the cost of making the rock record a matter of definition rather than investigation. This is done by codifying the absolute ages that make up the timescale, using *Global Stratotype Section and Points* (GSSPs) for the Phanerozoic and *Global Standard Stratigraphic Ages* (GSSAs) for the Precambrian (Reed, 2008a; 2008b; 2008c; 2008d). In other words, once ages are determined for each stratigraphic stage, those ages are set for all equivalent strata. One reason this new strategy has gained traction among geologists is their belief that more sophisticated methods, like cyclostratigraphy, provide the high-resolution dating needed to make such a proposal feasible.

We will discuss other stratigraphic methods in subsequent series. Creationists need to understand each of them, their role in supporting the timescale, and their strengths and weaknesses. We will describe each method, trace its development, and offer critiques of the methods and their underlying assumptions.

Cyclostratigraphy and Astrochronology

"Cyclostratigraphy is the study of astronomically forced cycles in the sedimentary record" (Miall, 2012, p. 11). It assumes that features of sediments and sedimentary rocks, especially those manifested in any cyclical manner, can be dated by linking those cycles to those on an astronomical "clock." *Astrochronology* is the development of that absolute "clock" based on Milankovitch cycles derived from the orbital mechanics of our solar system (Hinnov and Hilgen, 2012). The resulting astronomical timescale is

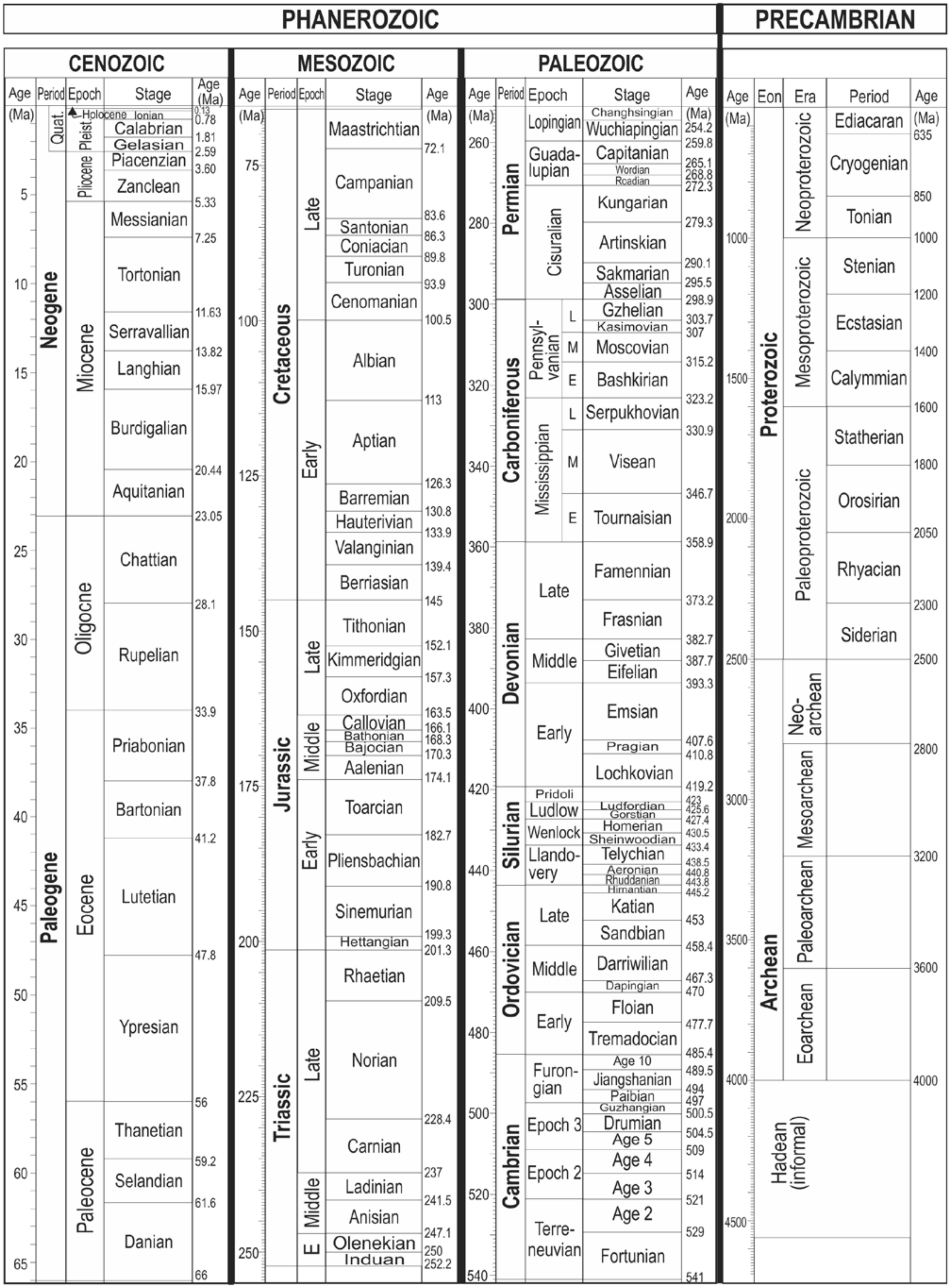


Figure 2. Geologic timescale based on International Commission on Stratigraphy's 2012 GTS. Traditionally, the combination of the relative position of the stages and their absolute age defined the timescale. Some, however, believe that since the absolute age defines the relative position, that the two are really one and the same.

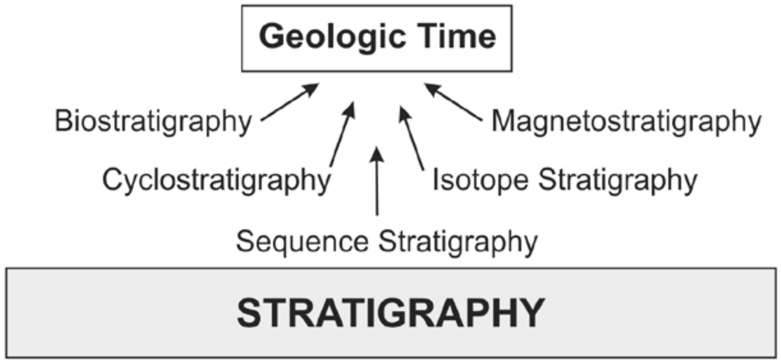


Figure 3. Geologic time rests on a variety of stratigraphic methods that are significantly more complex than the old biostratigraphy and radiometric dating.

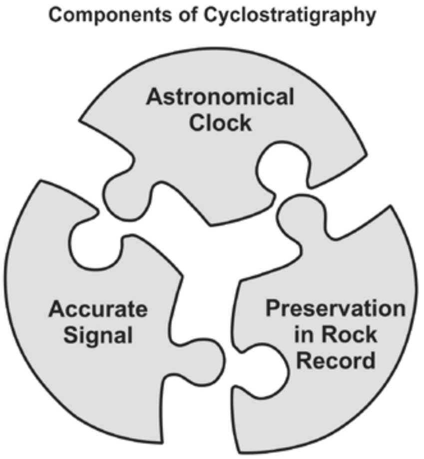


Figure 4. Cyclostratigraphy depends on the reality and accuracy of an astronomical clock, the accurate relay of the time signal to Earth via astronomically forced climate variation, and the preservation of these variations in sedimentary units that both capture this signal and are sufficiently sensitive to record its small changes in chemical, biogenic, and sedimentary fluctuations.

calibrated to sediments on Earth in a two-step manner: first through variations in sunlight, the *insolation signal*, which force climate change through time; and second, linking those climate changes to proxies in the rock record, such as the fractions of oxygen isotopes found in the sedimentary record. Because of the dependence on the extraterrestrial clock, the method has also been called "astronomical tuning" (Gradstein et al., 2004a). There are thus three critical components to cyclostratigraphy: (1) an astronomical clock, (2) the accurate transmission of its signal through sunlight fluctuations and climate variations, and (3) the preservation of that signal in the rock record (Figure 4). All three aspects must be understood to understand the overall method. But first we will demonstrate the importance of cyclostratigraphy to earth science.

Importance of Cyclostratigraphy

Cyclostratigraphy and its sister methods are driven by a need for increasing accuracy and precision in developing a chronology of Earth's past. This has led to the ongoing subdivision of the timescale into numerous stages of only a few million years in length; the old joke about dating methods yielding results that "give or take a few million years" is no laughing matter for the new timescale. The potential for severe cumulative error demands increasing accuracy and precision. This was one of the driving forces behind sequence stratigraphy and cyclostratigraphy, which claim error ranges in thousands, not millions, of years.

Currently, this presumed accuracy, enabled by the timing of various "Milankovitch cycles" (Gradstein et al., 2012) is calibrated to the timescale only through the Cenozoic with precision, but it continues to move back, making inroads into the Mesozoic and Paleozoic eras through "floating" timescales, or those that show a cyclic time signature for the section in question and can be linked to an absolute age on the timescale but are not yet linked to a continuous record of Milankovitch cycles covering all of time. A major goal of stratigraphers is to provide such linkage, allowing the correlation of the astronomical timescale with the sedimentary record as far back as they can take it (Gradstein et al., 2012).

Another important benefit of cyclostratigraphy is its support of the claim that the timescale is buttressed by multiple, overlapping, independent dating methods. Stung by criticisms of creationists, which focused on fossil succession and radiometric dating, geologists now believe that their new "clocks" add certainty to their chronology. Since cyclostratigraphy rests on the regularity of the motions of celestial bodies, it is perceived as being less vulnerable to criticism than other methods.

However, these two driving forces, increasing precision and an assumed support for other dating methods, are at odds with each other. If cyclostratigraphy is beneficial because it provides accurate dates within 10^4–10^5 years, and if radiometric dating and fossil dating cannot provide the same precision, then the benefit of having multiple, independent lines of evidence is limited. Since other geochronological methods cannot provide this precision, they cannot be calibrated to astronomical cycles within their tighter range of precision. For example, a radiometric age might only be accurate within 10^6 years. That is one to two orders of magnitude less precise than an astronomical cycle. Thus, the different methods cannot support the precision claimed in an overlapping fashion. At best, there can be agreement only within the range of dates provided by the *least* precise method.

Development of Cyclostratigraphy

The development of cyclostratigraphy and astrochronology is the subject of the next paper in this series, but a brief summary is appropriate here. The method dates back to the 1840s theory that glacial melting would affect sea level (Miall, 2012). Pioneers of the theory included Herschel (1830), Adhémar (1842), Lyell (1867), and Croll (1875). Geologists have always been interested in cycles in sedimentary rocks, and various researchers explored an astronomical connection (e.g., Bradley, 1929; Gilbert, 1895). This theory was boosted by the ability to quantify the cycles produced by orbital mechanics in the work of Milankovitch (1941). Using these cycles as a chronometer was first done for glacial sediments and later extended to older sedimentary rocks (e.g., Fischer, 1986). A variety of sedimentary proxies have been developed, allowing a linkage between the astronomical cycles and sedimentary layers. This has led to a new branch of stratigraphy.

> Over the past century, paleoclimatological research has led to wide acceptance that quasi-periodic oscillations in the Sun-Earth position have induced significant variations in the Earth's past climate. These orbitally forced variations influenced climate-sensitive sedimentation, and thereby came to be fossilized in the Earth's cyclic stratigraphic record. (Hinnov, 2004, p. 55)

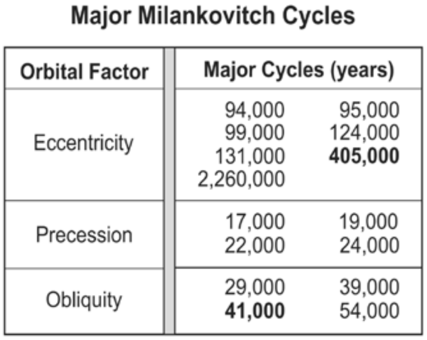
Basics of Cyclostratigraphy

Cyclostratigraphy rests on the idea that the amount of solar radiation reaching Earth at a given time is manifested in changes in preserved sedimentary rocks. Oscillations in orbital mechanics are thought to create regular cycles. Peaks and troughs in these cycles combine to create variations in the amount of solar heat reaching the lower atmosphere and ground. The Milankovitch theory combines three orbital parameters to generate a predicted curve of solar radiation and, by inference, cycles of climate change (cf. Oard, 1984).

Predicted cycles from astronomical models are then compared to sedimentary rocks (Hebert, 2014; Oard, 1997), especially those from deep-sea environments. Geologists use variations in oxygen and carbon isotopes, clay mineralogy, microfossil assemblages, sediment color, grain size, clay/dust abundance, microfossil abundance, and the percentage of silica, carbonate, and organic carbon in pelagic muds to calibrate sedimentary cycles to Milankovitch cycles.

In short, astronomical oscillation affects sunlight, sunlight affects climate, and climate is mirrored in sediments. It offers the advantages of potentially dating with greater precision and offering a new dating method that can support traditional biostratigraphy and radiometric dating. As recently as 2004, this process was still limited to relatively recent sediments (Gradstein, 2004, p. 4; Hinnov, 2004), but at present, progress has been extended back (Hinnov and Hilgen, 2012), and geologists seem determined to push the method deeper into geologic time. It is now claimed that these astronomical models are *accurately* tied to geochronology as far back as 40 Ma, and *reasonably* so back to 60 Ma (Hinnov and Hilgen, 2012). Each of the major variables results in variations with principal periods in the tens to hundreds of thousands of years (Figure 5). One of the most important for older strata is the 405-kyr eccentricity cycle:

> The 405 kyr eccentricity cycle has remained relatively stable over at least the past 250 million years. … This high-amplitude cycle is the consequence of gravitational interactions between Jupiter and Venus. … The large mass of Jupiter is responsible for the stability of the 405-kyr cycle, which has an estimated uncertainty of ~500 kyr at 250 Ma. Thus, this cycle can be used as a basic calibration period for cyclostratigraphy … The long-term goal of astrochronology is to assign ("tune") cyclostratigraphy to the appropriate 405-kyr bins. (Hinnov and Hilgen, 2012, p. 67)



Major Milankovitch Cycles

Orbital Factor	Major Cycles (years)	
Eccentricity	94,000	95,000
	99,000	124,000
	131,000	**405,000**
	2,260,000	
Precession	17,000	19,000
	22,000	24,000
Obliquity	29,000	39,000
	41,000	54,000

Figure 5. Major cycles derived from orbital mechanics. From Hinnov and Hilgen (2012).

Inside the Milankovitch Mechanism

The astronomical theory, or "Milankovitch mechanism," is based on changes in solar radiation due to the changing position of Earth relative to the sun, caused by cyclical variations in Earth's orbital geometry. These are assumed to be uniform through time, and complex astronomical models have been assembled to account for a number of variables (e.g. Laskar et al., 2004, 2011), although minor factors render the models inaccurate over longer periods of time greater than about 65 million years (Hinnov and Hilgen, 2012). The primary cycles are tied to three major variables: (1) changes in the *eccentricity* of Earth's orbit about the sun, (2) the *precession* of the equinoxes, and (3) changes in *obliquity*, or the tilt of Earth's axis (Figure 6; cf. Hebert, 2014; Milankovitch, 1941; Oard, 1984, 2005).

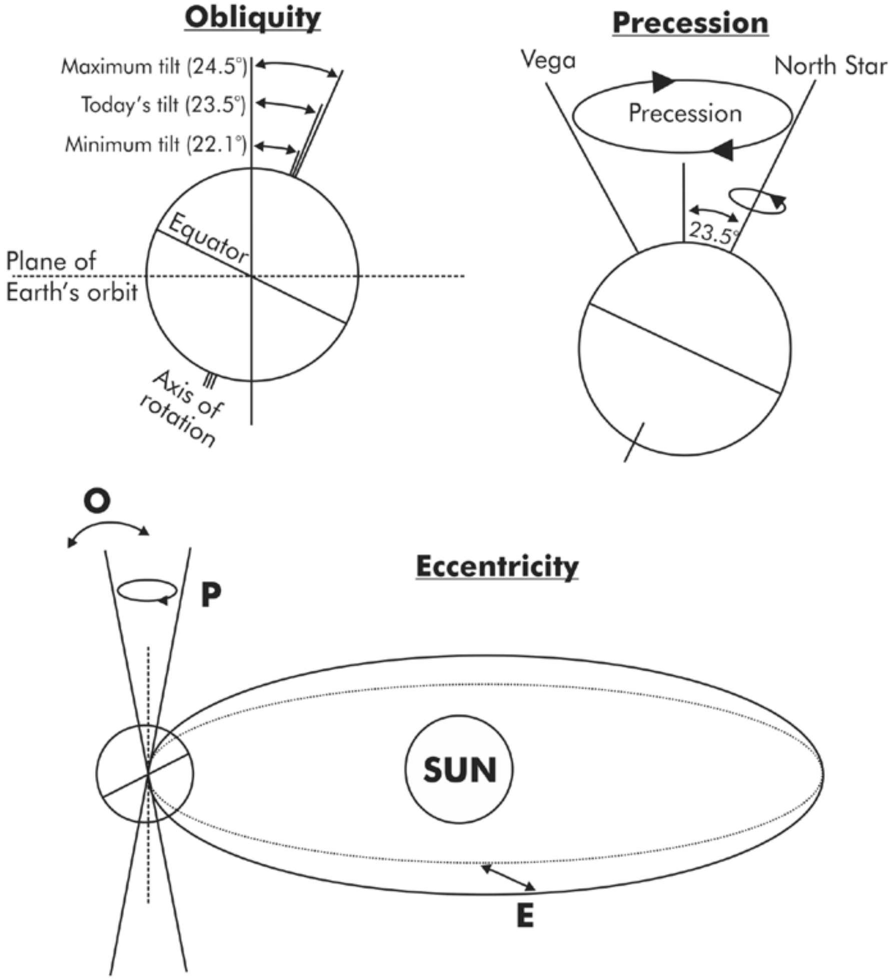


Figure 6. The Milankovitch theory claims to explain changes in the insolation signal by three orbital parameters: *Obliquity* (O), the tilt of Earth's axis of spin with respect to the ecliptic, with a dominant cycle of 41,000 years, with minor cycles of 29,000, 39,000, and 54,000 years; *Precession* (P), the wobble in Earth's spin that varies in principal cycles of 17,000, 19,000, 22,000, and 24,000 years; and *Eccentricity* (E), the variation in the elliptical shape of Earth's orbit, with principal periods of 95,000, 99,000, 124,000, 131,000, 405,000, and 2,260,000 years. Computer modeling relies on the 405,000-year sequence as a primary correlation marker for cyclostratigraphy. From Reed (2013).

Eccentricity Variation

Kepler showed that planetary orbits were elliptical. Eccentricity is a measure of the flatness of the ellipse or its deviation from a circle. An eccentricity of zero is a perfect circle, while an eccentricity of one is an ellipse so flat as to form a line. Presently, Earth's eccentricity is 0.017 and is caused by the gravitational pull of other planets. Earth's closest approach to the Sun is called the *perihelion* and the farthest distance is called the *aphelion*. Earth's perihelion occurs on January 3 at a distance of 91.5 million miles, while its aphelion is on July 4 (Figure 7) at 94.5 million miles, a difference of 3 million miles.

Based on an orbital mechanical extrapolation into the past, the eccentricity of Earth's orbit has been worked out for many millions of years. The eccentricity varies from near zero to a maximum of about 0.07. Figure 8 shows the change in the eccentricity for the past 2 million years (Vernekar, 1972). There are two major periods of oscillation, one at about 99,000 years and the second at approximately 405,000 years.

Variation of the Precession of the Equinoxes

The precession of the equinoxes is the rotation of the cardinal points—the equinoxes and solstices—around Earth's orbit. It is caused by two forces. The first causes the cardinal points to rotate clockwise along Earth's orbit due to the differential gravitational attraction by the sun and moon on Earth's poles and equatorial bulge. This force assumes a stationary elliptical orbit, but the orbit itself, the second force, actually rotates around the earth counterclockwise, but at a much slower rate, and is caused partly by the changing gravitational response of the other planets. Precession is seen more clearly using the reference point of the fixed stars. Over a long period of time, the axis of the earth's rotation wobbles like a spinning top (Figure 9).

One precessional cycle is defined as the time needed for the vernal or spring equinox to make one complete orbital rotation. This takes approximately 22,000 years. Currently, the vernal equinox is about March 20 (Figure 7), and it would take 11,000 years for this equinox to rotate through half of its orbit, through aphelion to the point where the autumnal equinox is now located. Then it would continue through perihelion to its current location in another 11,000 years.

The precession of the equinoxes depends on the eccentricity of the orbit. The eccentricity modulates the precession effect because it is the shape

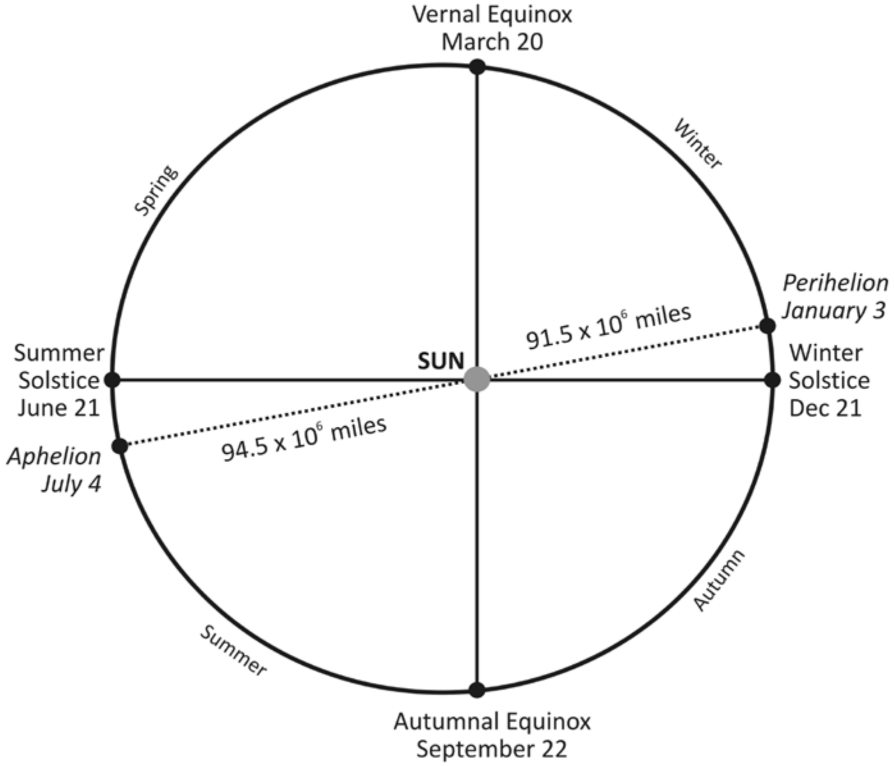


Figure 7. The current geometry of the earth's orbit around the sun. Modified from Imbrie and Imbrie (1979).

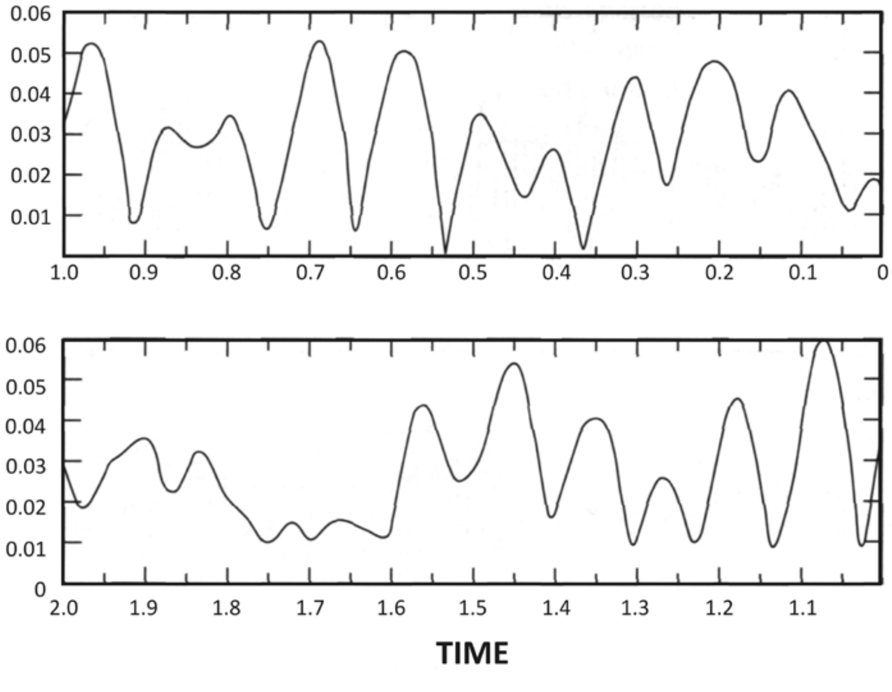


Figure 8. Variations in Earth's eccentricity for the past two million years. Modified from Vernekar (1972).

of the ellipse that determines the precessional change in solar radiation (Figure 10). For instance, if eccentricity were zero (a perfect circle), there would be no change in solar radiation from the precession of the equinoxes. As can be seen in figures 8 and 10, the period of low eccentricity around 1.7 million years ago had a slight precession change. On the other hand, when the eccentricity is high, around 0.6 about 1.1 million years ago (Figure 10), the precessional oscillations would have been quite large.

Obliquity (Tilt Cycle)

The third Milankovitch cycle is obliquity, or the tilt cycle. The current tilt of Earth's axis in relation to its plane of the *ecliptic* (the plane formed by the rotation of the earth around the sun) is 23.5°. Because of the gravitational pull of the other planets, the tilt wobbles a little from an angle of 22.1°to 24.5° with a major period of 41,000 years (Figure 11).

How Effective Is the Astronomical Clock?

However great the emphasis on these three orbital factors, the reality is that they have a small effect on the insolation signal (Elkibbi and Rial, 2001; Wunsch, 2004). Richard Kerr (2013, p. 599) states in *Science*: "For more than 30 years, climate researchers have been trying to figure out how slight changes in Earth's orbit could drive the major climate events of the last million years: the great ice ages." The question is whether or not the effect is sufficient to act as the primary driver of climate to the extent that the change would be preserved in sedimentary rocks. Furthermore, the changes in insolation are not constant over each hemisphere for a full year (Imbrie and Imbrie, 1979; Vernekar, 1972). The Milankovitch mechanism only changes the *seasonal and latitudinal distribution* of solar radiation. The precessional cycle mainly affects the *distribution* of the seasonal solar radiation and has the strongest effect in lower latitudes. For instance, when the warm half of the year shows a solar radiation minimum in the Northern Hemisphere, the winter compensates by an above normal change in solar radiation (Imbrie and Imbrie, 1979; Vernekar, 1972). Furthermore, the precessional cycle is out of phase between the hemispheres. While the Northern Hemisphere receives above-normal sunlight during summer, the Southern Hemisphere receives less because it is winter, and the tilt cycle causes insolation variations by latitude. When insolation is below average in high latitudes, it is above average in lower latitudes, but without any net change for the hemisphere as a whole.

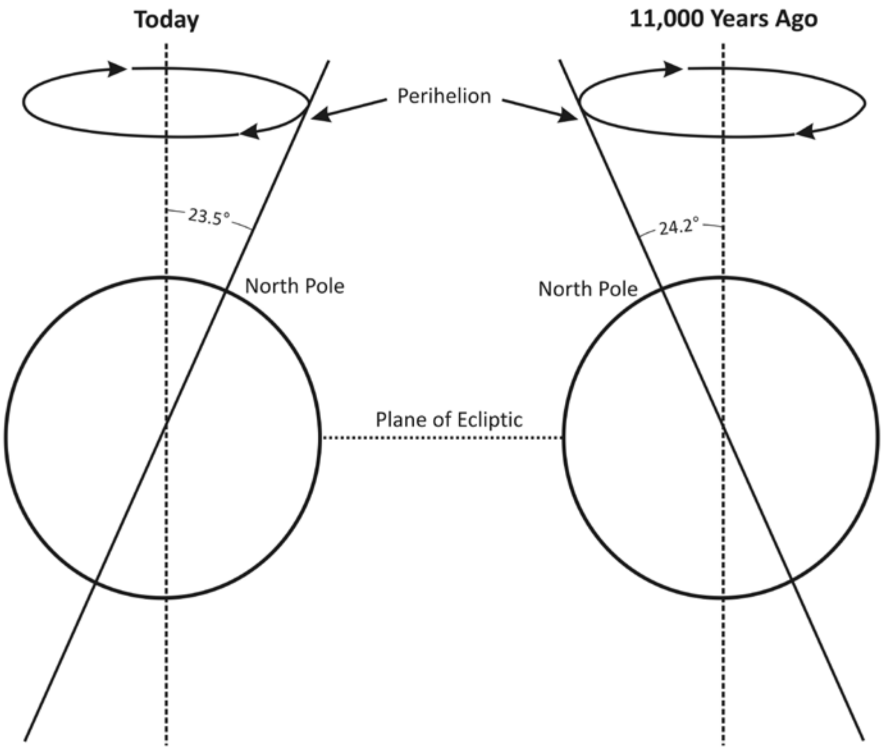


Figure 9. The change in Earth's axis of rotation, as seen from fixed stars, today and 11,000 years ago. Also shown is the change in tilt of Earth's axis during that time. Modified from Fodor (1982).

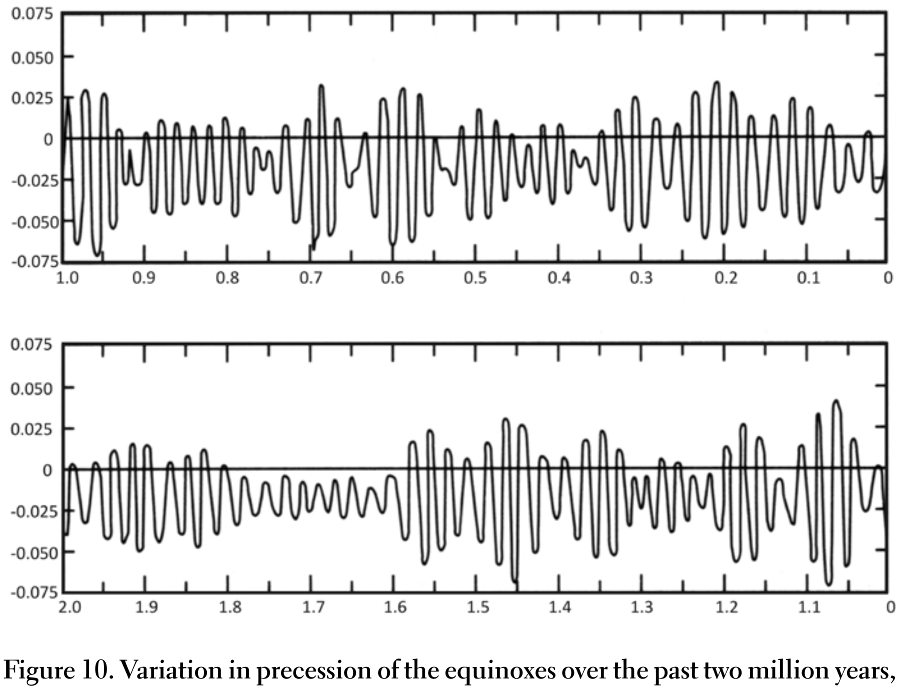


Figure 10. Variation in precession of the equinoxes over the past two million years, modulated by the change in the eccentricity of Earth's orbit. Time units (X axis) in hundreds of thousands of years. Modified from Vernekar (1972).

Preservation in Sedimentary Record

Geologists initially attempted to apply the idea of cyclical climate forcing on glacial advances, varves, and cyclothems. The breakthrough for cyclostratigraphy came during the various ocean drilling programs that began in 1975. Currently, the program has accumulated well, sampling, and seismic data for more than 350 locations, and has correlated cycles in cores from these wells to the astrochronological timescale (Hinnov and Hilgen, 2012). Obviously, this exercise requires proxies for climate change in sedimentary rocks. Over recent decades, a number of proxies have been used (Figure 12).

Summary

Cyclostratigraphy/astrochronology has become a major method in stratigraphy, responsible for finely tuned (10^4–10^5 years) geochronologic ages that have contributed to the increasing complexity and precision of the geologic timescale (Figure 2). At present, "firm" dates are available only back through the Cenozoic, but the trend clearly indicates that this will be pushed deeper in time within the next decades.

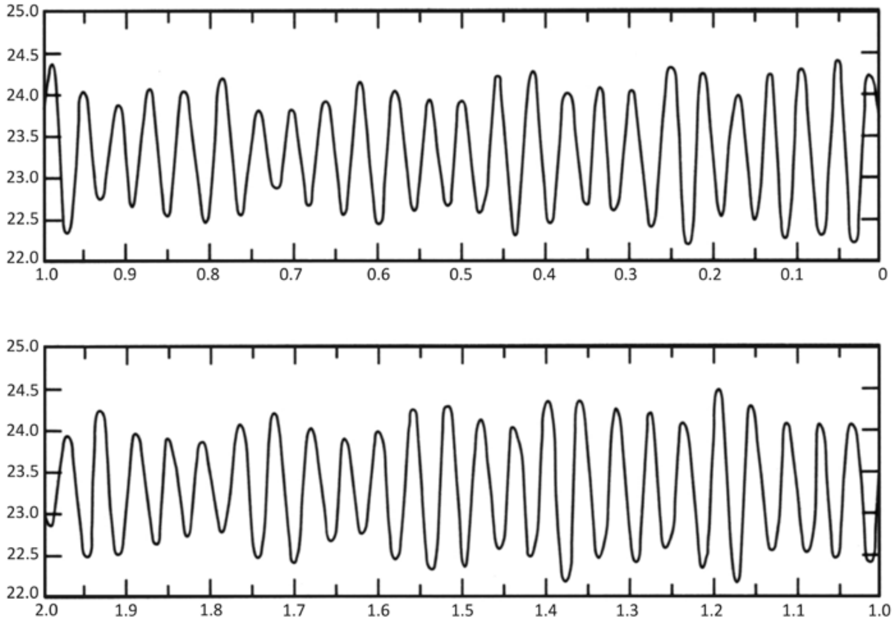


Figure 11. Variation in tilt of Earth's axis for past two million years. Time units (X axis) in hundreds of thousands of years. Modified from Vernekar (1972).

Proxies for Astrochronology in Sedimentary Rocks

Sed. Rate	Indicator	Climatic Effect
Independent	Oxygen isotopes	Temperature, salinity, eustasy, precipitation
Independent	Carbon isotopes	Productivity, redox, C-sequestration
Independent	Clay assemblages	Surface hydrology
Independent	Microfossil assemblages	Salinity, temperature
Dependent	% CoCO3, Si, CORG	Productivity
Dependent	Magnetic susceptiblity	Sedimentation rate
Dependent	Microfossil abundance	Productivity
Dependent	Clay/dust abundance	Surface hydrology, atmospheric circulation
Dependent	Lithofacies	Depositional environment
Dependent	Sediment color	Productivity, redox conditions
Dependent	Grain size	Erosion intensity, hydrodynamics

Figure 12. A number of climate proxies have been used to calibrate sedimentary sequences in an attempt to demonstrate astronomical forcing of deposition. From Hinnov and Hilgen (2012).

Cyclostratigraphy depends on the theory that cycles generated by orbital mechanics, especially with regard to eccentricity, precession, and obliquity, force climatic changes on Earth that are sufficiently powerful to be imprinted in sedimentary rocks through a variety of climatic proxies.

There can be no doubt that this method deserves more attention from creationists who wish to understand current advances in stratigraphy and the geologic timescale. In part II of this series, we will trace the historical development of cyclostratigraphy and astrochronology. In part III, we will critique the astronomical timescale, and part IV will conclude with a critique of cyclostratigraphy and its geological applications.

References

CRSQ: Creation Research Society Quarterly

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

Ager, D.V. 1973. *The Nature of the Stratigraphical Record*. Wiley, New York, NY.

Ager, D.V. 1993. *The New Catastrophism*. Cambridge University Press, New York, NY.

Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208:1095–1108.

Bradley, W.H. 1929. *The Varves and Climate of the Green River Epoch*. Professional Paper 158-E, 87–110. U.S. Geological Survey, Washington, DC.

Bretz, J.H. 1923. The channeled scabland of the Columbia Plateau. *Journal of Geology* 31:617–649.

Bretz, J.H. 1925. The Spokane flood beyond the channeled scablands. *Journal of Geology* 33:97–115, 236–259.

Cleland, C.E. 2013. Common cause explanation and the search for the "smoking gun." In Baker, V.R. (editor), *Rethinking the Fabric of Geology*, pp. 1–10. Geological Society of America Special Paper 502, Boulder, CO.

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

Elkibbi, M., and J.A. Rial. 2001. An outsider's review of the astronomical theory of the climate; is the eccentricity-driven insolation the main driver of the ice ages? *Earth-Science Reviews* 56:161–177.

Ferrusquía-Villafranca, I., R.M Easton, and D.E. Owen. 2009. Do GSSPs render dual time-rock/time classification and nomenclature redundant? *Stratigraphy* 6(2): 135–169.

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

Fodor, R.V. 1982. Frozen earth: explaining the ice ages. *Weatherwise* 35(3): 109–114.

Gentry, R.V. 1966. Cosmological implications of extinct radioactivity from pleochroic halos. *CRSQ* 3:17–20.

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

Gish, D. 1972. *Evolution: The Fossils Say No!* Master Books, San Diego, CA.

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

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

Gradstein, F.M., J.G. Ogg, and A.G. Smith. 2004b. Chronostratigraphy: linking time and rock. In Gradstein, F.M., J.G. Ogg, and A.G. Smith (editors), *A Geologic Time Scale 2004*, pp. 20–47. Cambridge University Press, Cambridge, UK.

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

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.

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

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*. Elsevier, Amsterdam, Netherlands.

Holmes, A. 1960. A revised geologic timescale. *Transactions of the Edinburgh Geological Society* 17:183–216.

Hooykaas, R. 1963. *The Principle of Uniformity in Geology, Biology, and Theology*, second impression. E.J. Brill, London, UK.

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

Kerr, R.A. 2013. How to make a great ice age, again and again and again. *Science* 341:599.

Kravitz, Gadi. 2013. The thermodynamics time arrow and the logical function of the uniformity principle in geohistorical explanation. In Baker, V.R. (editor), *Rethinking the Fabric of Geology*, pp. 19–40. Geological Society of America Special Paper 502, Boulder, CO.

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.

Laskar, J., A. Fienga, M. Gastineau, and H. Manche. 2011. La2010: a new orbital solution for the long-term motion of the Earth. *Astronomy & Astrophysics* 532(A89): 1–15.

Lyell, C. 1867. *Principles of Geology*, tenth edition. John Murray, London, England.

Miall, A.D. 2004. Empiricism and model building in stratigraphy: the historical roots of present-day practices. *Stratigraphy* 1(1): 3–25.

Miall, A.D. 2012. Sophisticated stratigraphy. Preprint of a contribution to the volume celebrating the 125th anniversary of the Geological Society of America.

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.

Mortenson, T. 2004. *The Great Turning Point: The Church's Catastrophic Mistake on Geology before Darwin*. Master Books, Green Forest, AR.

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

Oard, M.J. 1997. Are pre-Pleistocene rhythmites caused by the Milankovitch mechanism? *Journal of Creation (Creation Ex Nihilo Technical Journal)* 11(2): 126–128.

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.

Reed, J.K. 2008a. Toppling the timescale, part I: evaluating the terrain. *CRSQ* 44:174–178.

Reed, J.K. 2008b. Toppling the timescale, part II: unearthing the cornerstone. *CRSQ* 44:256–263.

Reed, J.K. 2008c. Toppling the timescale, part III: madness in the methods. *CRSQ* 45:6–17.

Reed, J.K. 2008d. Toppling the timescale, part IV: assaying the golden (FeS_2) spikes. *CRSQ* 45:81–89.

Reed, J.K. 2010. Untangling uniformitarianism, level I: a quest for clarity. *Answers Research Journal* 3:37–59.

Reed, J.K. 2011. Untangling uniformitarianism, level II: actualism in crisis. *Answers Research Journal* 4:203–215.

Reed, J.K. 2013. *Rocks aren't Clocks*. Creation Book Publishers, Powder Springs, GA.

Reed, J.K., and E.L. Williams. 2012. Battlegrounds of natural history, part II: actualism. *CRSQ* 49:135–152.

Romano, M. 2015. Reviewing the term uniformitarianism in modern Earth sciences. *Earth-Science Reviews* 148:65–76.

Torrens, H.S. 2002. Some personal thoughts on stratigraphic precision in the twentieth century. In Oldroyd, D.R. (editor), *The Earth Inside and Out: Some Major Contributions to Geology in the Twentieth Century*, pp. 251–272. Special Publication 192, Geological Society, London, UK.

Vernekar. A.D. 1972. Long-period global variations of incoming solar radiation. *Meteorological Monograph* 12(34): 1–21 and tables.

Whitelaw, R.L. 1968. Radiocarbon confirms biblical creation (and so does Potassium-Argon). *CRSQ* 5:78–83.

Whitelaw, R.L. 1970. Time, life, and history in the light of 15,000 radiocarbon dates. *CRSQ* 7:56–71.

Woodmorappe, J. 1979. Radiometric geochronology reappraised. *CRSQ* 16:102–129.

Wunsch, C. 2004. Quantitative estimates of the Milankovitch-forced contribution to observed Quaternary climate change. *Quaternary Science Reviews* 23:1001–1012.