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Cycles in Earth Sciences, *Quo Vadis*? Essay on Cyclicity Concepts in Geological Thinking and their Historical Influence on Stratigraphic Practices

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Abstract

The archetype of a cycle has played an essential role in explaining observations of nature over thousands of years. At present, this perception significantly influences the worldview of modern societies, including several areas of science. In Earth sciences, the concept of cyclicity offers simple analytical solutions in the face of complex events and their respective products, both in time and space. Current stratigraphic research integrates several methods to identify repetitive patterns in the stratigraphic record and to interpret oscillatory geological processes. This essay proposes a historical review of the cyclic conceptions from the earliest phases in Earth sciences to their subsequent evolution into current stratigraphic principles and practices, contributing to identifying opportunities in integrating methodologies and developing future research mainly associated with quantitative approaches.

1 Introduction

> *Nature vibrates with rhythms, climatic and dystrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-marks, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of composite rhythms— day and night, calm and storm, summer and winter, birth*

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> *and death—such as these are sensed in the brief life of man. But the career of the Earth recedes into a remoteness against which these lesser cycles are as unavailing for the measurement of that abyss of time as would be for human history the beating of an insect's wing. We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the Earth […] Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves which have pulsed through geologic time (Barrell, 1917, p. 746).*

Cycles, rhythms, oscillations, pulsations, repetitions, or periods are examples of terms frequently used in the geological literature that reflect a profound influence of the conception of cyclicity in the Earth sciences. This conception is widespread in many areas of knowledge (e.g., Puetz, 2009).

> *Explanations of sound, tone, and harmonics were among the first elements of modern physical science. This early success in description and prediction of periodic astronomical events together with an understanding of periodicity related to vibration in the production of sounds led scientists to seek periodicities elsewhere in the natural world. Today the list is extensive for phenomena in which cycles have been studied. It includes sunspot activity, tides and ocean waves, earth tides, music, human speech, tree-ring growth, animal population changes, brain waves, heart rhythm, chemical bonding forces, climatic activity, economic growth, light and other electromagnetic wave phenomena, and geological events. (Preston and Henderson, 1964, p. 415)*

From a historical perspective, the cycle archetype is found in several ancient traditions, attested, for instance, in lithic monuments such as Stonehenge, built-in alignment with solar and lunar cycles (Hawkins, 1963), and religious practice regulated by the seasons and their astronomical markers (Boutsikas and Ruggles, 2011). The word "cycle" derives from the Greek term "κψκλοσ", used to describe any circular body, as well as any circular and perpetual movement of successive events or phenomena, which return to their original position. Ancient Greeks described repetitive patterns to characterize the organization of almost all known processes. This idea of uniformity and continuity has been influenced by empirical observations of phenomena such as day and night, changes in the moon phase, and seasons (Nelson, 1980).

Whether through a historical heritage or from various discoveries made over time, examples are plentiful to demonstrate that cycles are used to describe geological processes and products containing some characteristic repetitive patterns in the geological record. Sometimes this concept is vague, without defining an order, or a periodicity, as is the case with the rock cycle (e.g., Gregor, 1992). This geological postulate determines that the rock record itself is a product of a fundamental cycle in which igneous, sedimentary, and metamorphic rocks are continuously turned into one another. However, the current understanding of the processes that integrate the Earth system theorizes the existence of periodical processes, at different timescales, that range from the complex dynamics of the Earth's interior (e.g., Mitchell et al., 2019) to the astronomical forces that make our planet interact with neighboring celestial bodies (e.g., Hinnov, 2018). In this way, the occurrence of "true cycles", which correspond to an orderly, repetitive progression of events that is unlikely to occur by chance, is increasingly being demonstrated.

What could be interesting to add is that the concept of cyclicity has been explored also in non-geological context. Giambattista Vico (1668 – 1744), for example, introduced a cyclical idea of history ("corsi" and "ricorsi storici").

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As illustrated in Joseph Barrell's (1869 – 1919) quote, "the stratigraphic series constitutes a record, written on tablets of stone," of these cycles that control the Earth system. Current stratigraphic research integrates several systematic methods to identify and interpret repetitive units of the sedimentary record (e.g., sequence stratigraphy and cyclostratigraphy). Henceforward, the concept of cyclicity has been essential in promoting geological knowledge and constitutes one of the pillars of stratigraphy (e.g., Schwarzacher, 2000).

In this context, the comprehension of the origin and the evolution of the cyclicity concepts in stratigraphy is quite relevant and opportune. The following synthesis reviews the main works that use these concepts to interpret geological processes and their imprint in the stratigraphic record. It goes from a historical review to the current state of the art in stratigraphic principles and practices.

2 Cyclicity of Geological Processes

Studies of cyclicity in geological processes commonly seek to find periodicities in data series and explain them in terms of known natural phenomena (Preston and Henderson, 1964). The current demonstration of recurring global processes, with regular periodicity, illustrates the search for "longer rhythms whose very existence was unknown until man by the light of science sought to understand the Earth" (Barrell, 1917, p. 746). In a recent investigation into the recurrence and synchronicity of global geological events, Rampino et al. (2021) determined the existence of an Earth pulsation. The authors analyzed 89 significant and well-dated geological events over the past 260 million years, including marine and non-marine biological extinctions, major oceanic anoxic events, flood-basalt eruptions, sea-level fluctuations, pulses of intraplate magmatism, and times of changes in seafloor-spreading rates and plate reorganization. Moving-window analysis evidences the presence of ten peaks or clusters in the number of events (Figure 1A). Between these peaks, the number of events approaches zero. Fourier analysis shows that the highest peak occurs at 27.5 Myr (99% confidence), with a secondary signal at 8.9 Myr (Figure 1B). Similar cycles have been determined in other studies analyzing climate change (e.g., Shaviv et al., 2014), sea-level oscillations (e.g., Boulila et al., 2018), extinctions (e.g., Clube and Napier, 1996), and Earth's tectonic behavior (e.g., Müller and Dutkiewicz, 2018). The common finding of several authors is that these cyclical events are global, correlative, and tightly coupled. According to Rampino et al. (2021, p. 6), the correlation and cyclicity of these episodes point to an essentially periodic and coordinated geological record, whose origin "may be entirely a function of global internal Earth dynamics affecting global tectonics and climate, but similar cycles in the Earth's orbit in the Solar System and in the Galaxy might be pacing these events".

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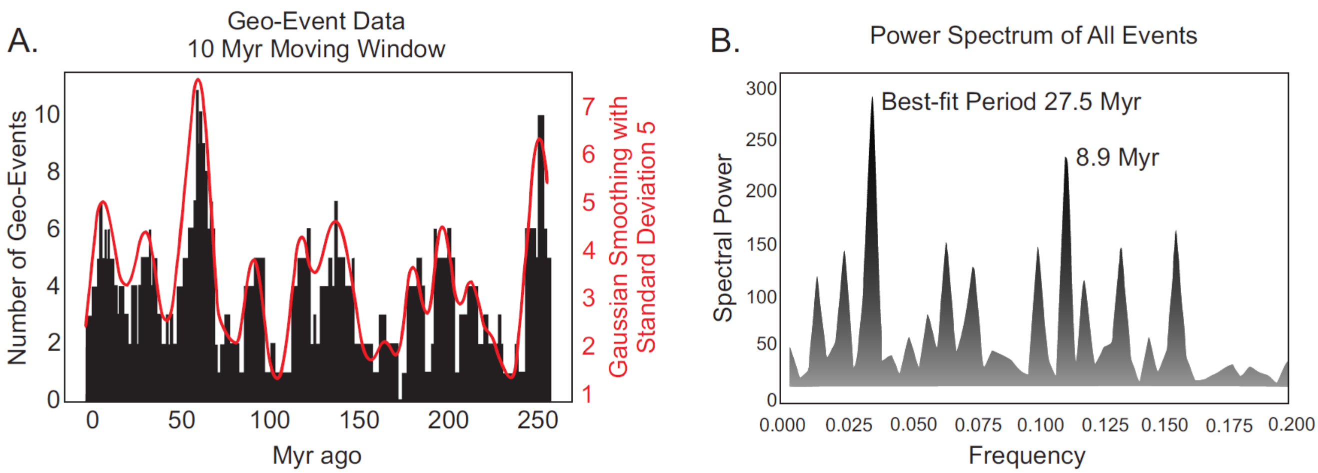

Figure 1. A - Analysis of the ages of 89 geologic events using a 10-Myr moving window centered every 0.5 Myr, with the number of occurrences that fall within the moving window computed at 1-Myr intervals. Ten clusters (peaks) are visible. In red, the Gaussian smoothing with a standard deviation of 5 Myr centered at every 0.1 Myr, with ten peaks. B - Fourier transform results show the highest peak in 27.5 Myr, and a strong secondary period occurs at 8.9 Myr (modified from Rampino et al., 2021).

2.1 The Astronomical Clock

> *Periodicity is one of the fundamental phenomena recorded by observant man. Cycles associated with astronomical events were among the first natural phenomena described with sufficient precision and generality that such events could be predicted for the future. Even for primitive societies, one measure of their level of scientific understanding is the accuracy of their calendars. (Preston and Henderson, 1964, p. 415)*

The roots of the geologists' appeal for the periodicity of natural processes may be found in the Aristotelian worldview, which expanded the human experiences of the cyclic phenomena, such as day and night, tides, and seasons (Dott, 1992). In one of the first essays about the history of geology, the classic book *Principles of Geology* by Charles Lyell (1797 – 1875) mentions this possible relationship.

> *When we consider the acquaintance displayed by Aristotle, in his various works, with the destroying and renovating powers of nature, the introductory and concluding passages of the twelfth chapter of his "Meteorics" are certainly very remarkable. In the first sentence, he says, "the distribution of land and sea in particular regions does not endure throughout all time, but it becomes sea in those parts where it was land, and again it becomes land where it was sea; and there is a reason for thinking that these changes take place according to a certain system, and within a certain period." The concluding observation is as follows: " As time never fails, and the Universe is eternal, neither the Tanais, nor the Nile, can have flowed forever. The places where they rise were once dry, and there is a limit to their operations, but there is none to time. So also of all other rivers; they spring up, and they perish; and the sea also continually deserts some lands and invades others. The same tracts, therefore, of the Earth are not, some always sea, and others always*

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> *continents, but everything changes in the course of time." It seems, then, that the Greeks [...] deduced, from their own observations, the theory of periodical revolutions in the inorganic world. (Lyell, 1835, p. 21-22).*

Lyell (1835) discusses the intellectual advance of ancient civilizations, such as the Hindis and the Egyptians, and highlights mainly Greek philosophy that considered the course of events on the planet continually repeated in perpetual vicissitude, mainly influenced by the knowledge of astronomy. The various Greek contributions to scientific knowledge reflect a strong sense of observation of astronomical cycles. Among the many examples, the studies of celestial phenomena and their potential for temporal calibrations stand out. Hipparchus of Nicaea (190 – 120 BC), considered by many to be the greatest of Greek astronomers, used mathematical bases to determine the length of the year and the recurrence of eclipses with relatively high precision. Credit must be given to his conclusions about the motion of the stars, which Nicolau Copernicus (1473 – 1543) later attributed to the "precession of the equinoxes" (Hockey et al., 2007). Twenty centuries later, these concepts would guide the research on orbital cyclicity used to construct paleoclimatic, cyclostratigraphic, and astrochronological models (e.g., Hinnov, 2018).

2.1.1 The Beginning of Glacial Theories

The discovery of glacial cycles is among the greatest ever made in Earth sciences. In 1837, Louis Agassiz (1807 – 1873), then president of the Swiss Society of Natural Sciences, presented ideas that shocked his peers (Imbrie and Imbrie, 1979). Agassiz (1840) argued that large fragments of rock, which occurred erratically in the region of the Jura mountains, far from their areas of origin, were evidence of an ancient ice age. Although these ideas were not necessarily original, having been put forward in the 18th century by James Hutton (1729 – 1797) and Bernard Friederich Kuhn (1762 – 1825), Agassiz brought "the glacial theory of scientific obscurity to the public eye" (Imbrie and Imbrie, 1979, p.21).

Although the conception of an ice age was fundamentally as being catastrophic, its development took place on fertile ground for ideas of the cyclical nature of geological processes. One of the pioneers, before Agassiz's work, was Jens Esmark (1762 – 1839). Esmark (1824) showed that massive glaciers covered different parts of Europe, sculpting the landscape, and proposed the eccentricity of the Earth's orbit as a hypothesis that caused climate change. Influenced by William Whiston's (1667 – 1752) contributions about the elliptical orbit, which would periodically place Earth far from the sun, Jens Esmark combined these findings into a consistent theory (Hestmark, 2017). The dissemination of such ideas fostered the scientific debate that continues to the present day. Research into the relationship between recurrent glaciations and orbital cycles has advanced significantly with the contributions of Joseph Alphonse Adhemar (1797 – 1862) and James Croll (1821 – 1890).

Adhémar (1842) sought to explain glaciations by reinforcing the hypothesis of orbital controls, especially the precession of the equinoxes. In his book *Les Révolutions de la Mer, Déluges Périodiques*, he argues that the glacial periods alternated between the hemispheres, with two glaciations – one to the north and one to the south – every 23 kyr. Anticipating what is now known as thermohaline circulation, he introduced the effects of large-scale ocean currents, which link the planet's south and north poles, to explain the phenomenon of melting ice (Berger, 2012).

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James Croll's works stood out for defending the astronomical theory of glacial periods based on rigorous mathematical reasoning, significantly influenced by the astronomer Urbain Leverrier (1811 - 1877) and his research on orbital cyclicity. Croll sought to demonstrate that precession variation, modulated by eccentricity, drastically affects the intensity of radiation received by the Earth during each season of the year (Imbrie and Imbrie, 1979). Thus, he defended the origin of glaciations based on this seasonal effect. Furthermore, Croll considered the possibility of atmospheric amplification of orbital cycles through albedo effects as the snow caps grow and of amplifying orbital effects through ocean circulation (Paillard, 2001). In 1875, in the book *Climate and* Time, Croll updated his theory considering the variations in the inclination of the Earth's axis (obliquity cycle). Unfortunately, without further information on the timing of these variations, his study could not provide definitive answers (Imbrie and Imbrie, 1979).

In the mid-nineteenth century, also the effects of glacial cycles were studied, mainly on sea-level fluctuations. MacLaren (1842), for example, influenced mainly by the work of Agassiz, suggested that melting and reconstruction of the ice sheets that covered continents during glaciation should cause significant variations in the volume of the ocean. He estimated that these variations would reach magnitudes of 100 to 200 meters, closely anticipating the current understanding of glacioeustasy (e.g., Sames et al., 2020). Jamieson (1865) proposed another glacial mechanism for the relative change in sea level. From his investigations in Scotland, he suggested that the weight of the ice caps must have depressed part of the crust during the glaciation, which would return to its original position during the thaw (isostatic rebound).

2.1.2 Milankovitch and the Definitive Return of Astronomical Climate Models

The legacy of Croll's work served as a foundation for the Serbian Milutin Milankovitch (1879 – 1958). Milankovitch is one of the most well-known pioneers of planetary climatology, especially for finding a mathematical solution to correlate orbitally controlled insolation with the ice ages (Milankovitch, 1941; Paillard, 2001; Figure 2).

Milankovitch (1941) calculated the glacial-interglacial climatic oscillations as a function of solar radiation incident at the top of the atmosphere (insolation) for the last 600 kyr. While his predecessors used only eccentricity and precession, Milankovitch also included obliquity in his calculations. The triumph of Milankovitch's work was the precision, which could be tested with geological data for validation. The variations in solar radiation produce changes between colder (lower insolation rates) and warmer global climatic periods (higher insolation rates), which then influence atmospheric, hydrological, oceanographic, biological, and sedimentological processes on the Earth surface.

Some geologists accepted that the curves proposed by Milankovitch fit the geological record. However, many others disagreed, discrediting astronomical research, remaining skeptical until studies of deep-sea cores and isotopic research started (Fischer, 2012). According to the Milankovitch model, Emiliani (1955, 1966, 1978) determined that ocean temperatures fluctuated, based on a record of oxygen isotope ratios in calcitic fossils. Later, Shackleton (1967) improved the interpretation of variations in oxygen isotope ratios, suggesting that they reflect oscillations in the total volume of ice sheets during glacial cycles. Nowadays, Milankovitch's work is an essential element of deductive analysis and has become the keystone of cyclostratigraphy and astrochronology (e.g., Strasser et al., 2006). Astronomical solutions are calculated with ever-higher precision for the deep

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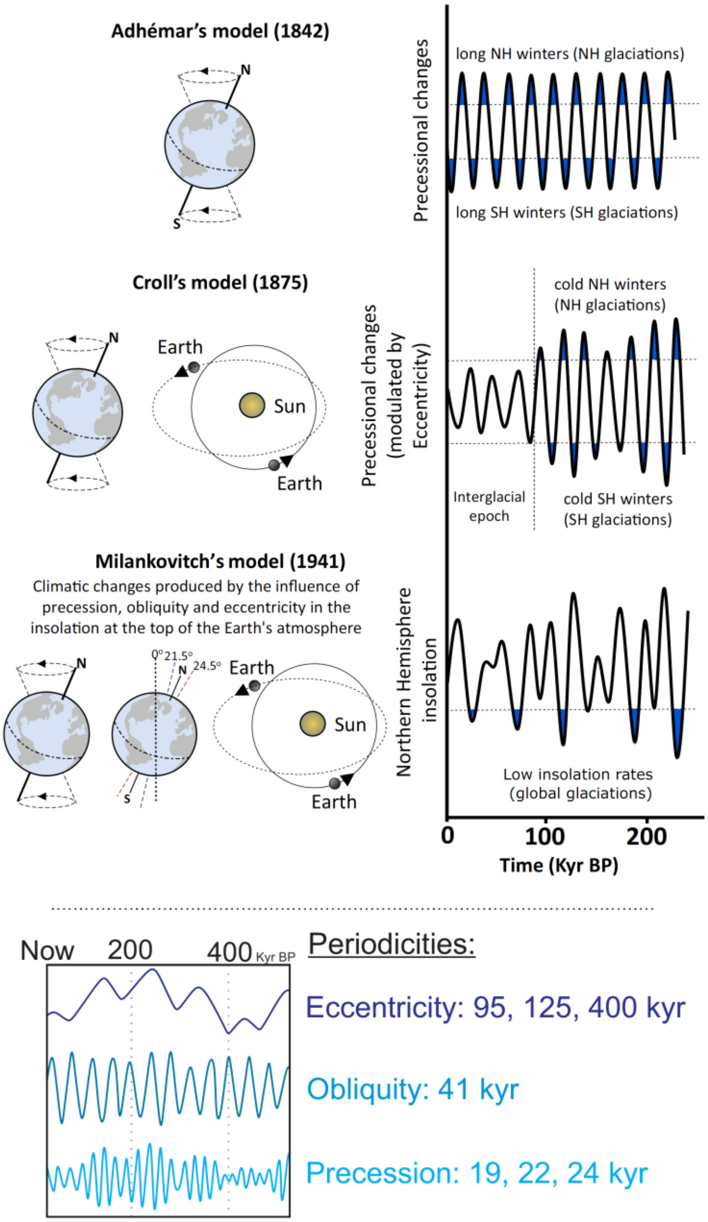
geological past (e.g., Berger et al., 1989; Laskar et al., 2011; Hinnov, 2018), and Milankovitch cycles are used to improve the geological time scale continually (e.g., Gradstein et al., 2021).



190 **Figure 2. Orbital models for glacial cycles. Adhémar's model considers only precession to explain cyclic glaciations alternating between hemispheres. Croll's model considers the interferences of eccentricity. The last is Milankovitch's model, a pioneer in determining the insolation calculated from all orbital parameters (modified from Paillard, 2001).**

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2.1.3 Astronomical Forcings on the Earth System

Many astronomical cycles leave a recognizable imprint in the geological record (e.g., House, 1995, Figure 3), ranging from twice-daily (such as tides; e.g., Kvale, 2006) to hundreds of millions of years (such as the vertical oscillation of the solar system across the galactic plane, and its association with impact episodes and mass extinction events on Earth; e.g., Randall and Reece, 2014). The geochronological value of these astronomical cycles has been recognized by many authors, which has led to the rise of astrochronology (Hinnov, 2018). Astronomical dating helps reconstruct the global climate history (e.g., Westerhold et al., 2020) and is now a significant element of the geological time scale (e.g., Walker et al., 2013; Gradstein et al., 2021).

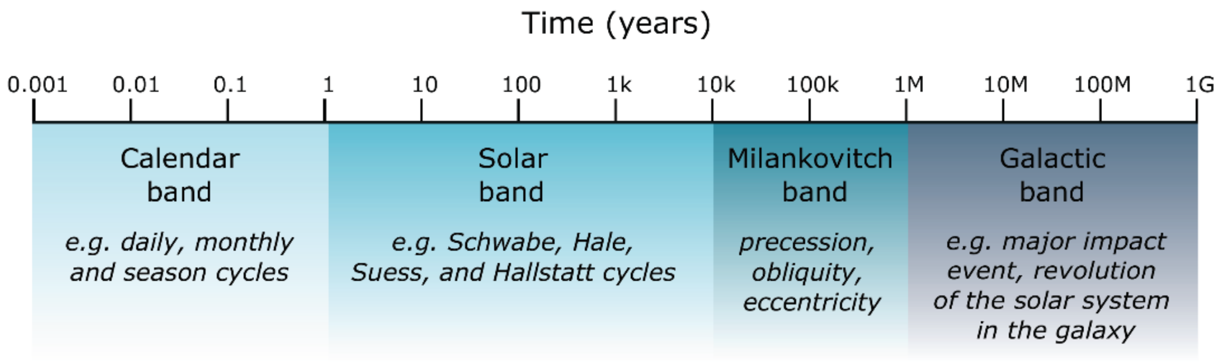

Figure 3. Logarithmic table of the astronomical cycle frequencies (adapted from House, 1995).

In addition to the buildup and melting of ice on the polar caps during icehouse conditions, astronomical cycles in the Milankovitch frequency band are forcing global processes also during greenhouse times (e.g., Schulz and Schäfer-Neth, 1998; Boulila, 2018; Strasser, 2018; Wagreich et al., 2021). Geological records in different parts of the world suggest a strong correlation between orbital cycles and global sea-level fluctuations. The eustasy associated with astronomical forcing on Earth's climate (Figure 4a) includes the exchange of water between the ocean and terrestrial stores, either in the form of ice (glacioeustasy; Figure 4A) or underground and surface reservoirs (aquifereustasy and limnoeustasy; Figure 4B), and also thermally-induced volume changes of the oceans (thermoeustasy; Figure 4C). During icehouse conditions, glacioeustasy predominates with high-amplitue sea-level fluctuations, while in a greenhouse world amplitudes are minor (e.g., Wilson 1998; Séranne, 1999; Sames et al., 2016; Figure 5).

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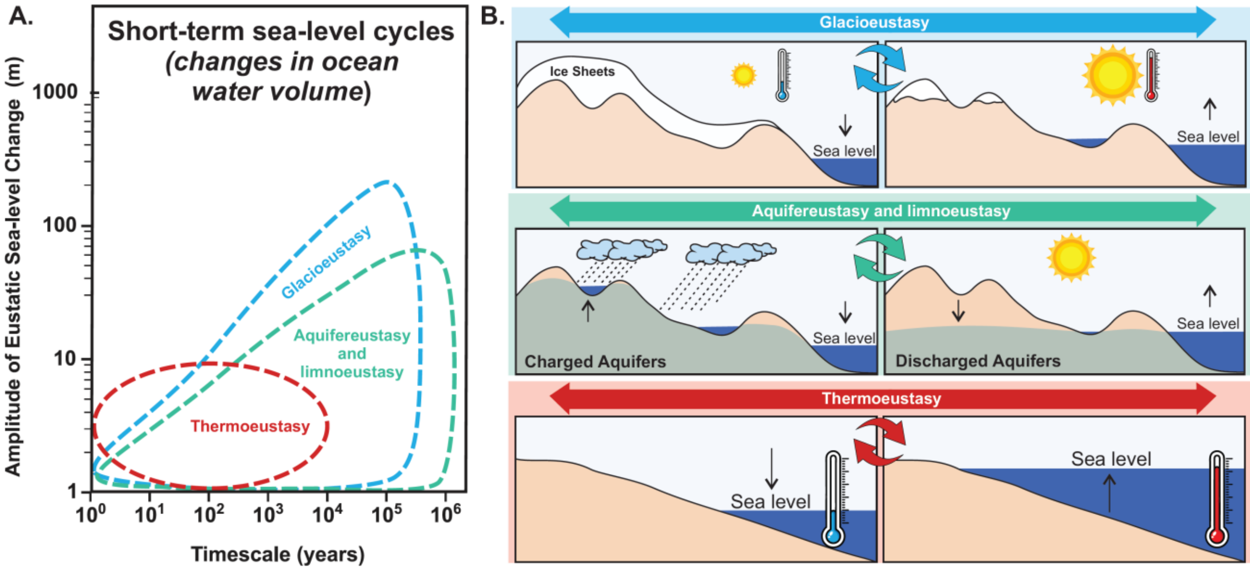

Figure 4. A - Log-scale diagram of the timing and amplitudes of the main mechanisms that control "short-term" sea-level variations. The values represented must be considered as averages. (modified from Sames et al. 2016). B - Schematic diagrams representing the processes that promote changes in sea level (glacioeustasy, aquifereustasy + limnoeustasy, and thermoeustasy) during climate changes induced by orbital cycles.

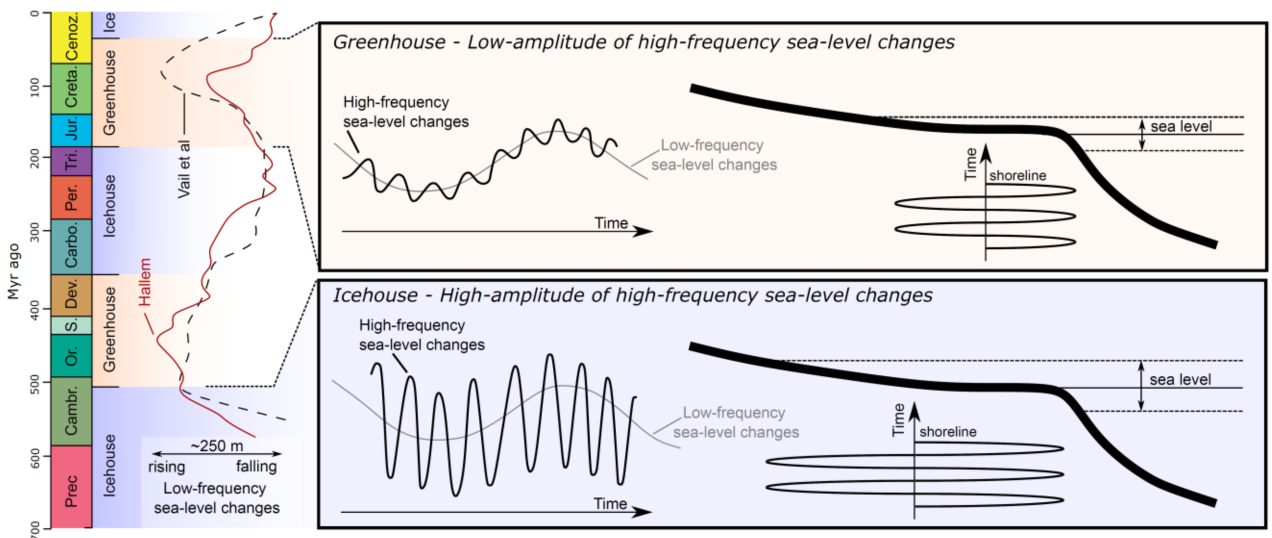

Figure 5. Changing frequencies and amplitudes of eustasy. In icehouse periods, these cycles have a high amplitude, mainly due to the effects of glacioeustasy. Eustatic oscillations have lower amplitude in greenhouse periods since there is no significant glacial effect (modified from Wilson, 1998; Séranne, 1999).

2.2 The internal gears of geodynamics

In the eighteenth century, during the Scottish Enlightenment, James Hutton (1726 – 1797) described the geological record observed in the landscape as a product of the continuous alternation of uplift, erosion, and depositional processes. The

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emergence of geology as an individualized science is currently linked to James Hutton's "Theory of the Earth", which described the Earth as a body that acts cyclically over geological time (Chorley et al., 2009).

This uniformitarian conception has a cyclical approach, which considers a priori that geological processes present repetitive patterns (O'Hara, 2018). The most significant contributor to the spread of uniformitarian thinking, Charles Lyell, presented a fascinating tale of the Earth's internal oscillating processes. He visited The Macellum of Pozzuoli (also known as Serapis Temple – Figure 6A) in the Italian region of Campania several times, highlighting this Roman ruin in an illustration on the frontispiece of the "Principles of Geology" (Figure 6B). In the middle portion of the three remaining marble pillars, there are borings left by marine lithophaga bivalves. According to Lyell, it is "unequivocal evidence that the relative level of land and sea has changed twice at Puzuolli, since the Cristian era, and each movement both of elevation and subsidence has exceeded twenty feet" (Lyell, 1835, p. 312). This variation of relative sea level identified by Lyell is now understood as a product of bradyseism, which corresponds to vertical ground movements (Figure 6C) caused by successive filling and emptying of magmatic chambers in volcanic areas (Parascandola, 1947; Bellucci et al., 2006; Lima et al., 2009; Cannatelli et al., 2020).

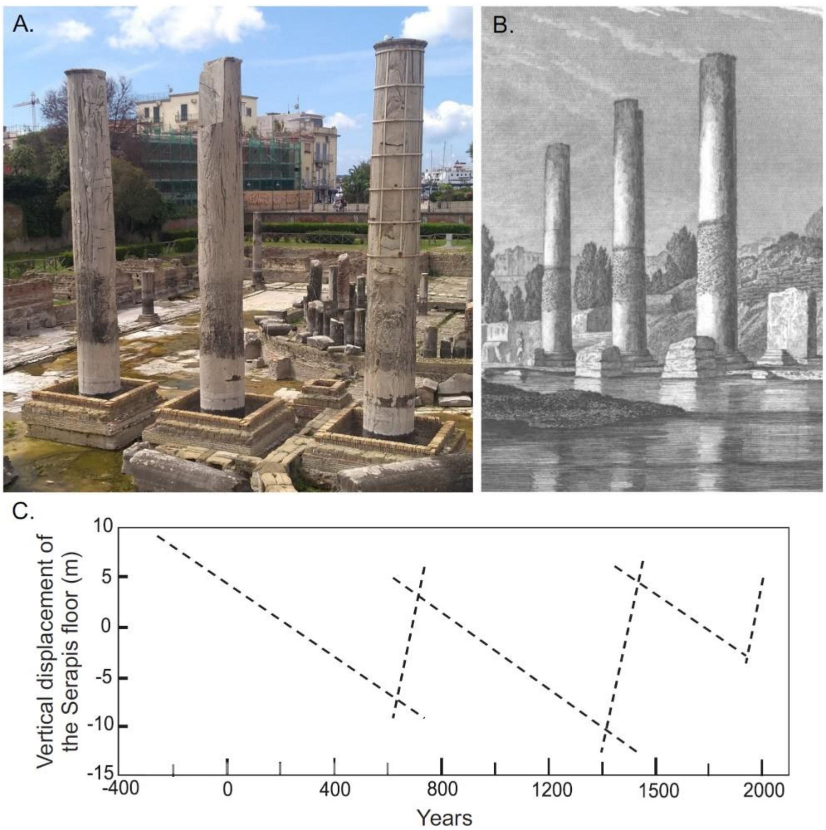

Figure 6. Roman ruins of the Serapis Temple (Macellum of Pozzuoli), in Pozzuoli, Italy: A. Recent picture. B. The illustration on the frontispiece of volume I of *Principles of Geology* (Lyell, 1835). Both highlight the rough texture of the intermediate portion of the columns where bivalve wear is evident, indicating marine transgression after the Temple's construction. C. Vertical movements of the Serapis Temple show an alternating pattern of elevation and subsidence produced by bradyseism (modified from Bellucci et al., 2006).

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The search for processes in the Earth's internal dynamics, and their relationship to sea-level variations, continued for many years after Hutton and Lyell. However, such research focused on finding diastrophic rhythms at large temporal and spatial scales, as Barrell (1917) mentioned, "those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras".

2.2.1 Diastrophic Theories and the Birth of Eustasy

The 18th and 19th centuries were the most scientifically active for the nascent discipline of geology. During this period, Earth's contraction was the leading theory for the origin and evolution of its morphology, such as mountain ranges. According to this conception, the Earth's radius diminished with time due to internal cooling, causing the crust to wrinkle. The theory of the Earth's cooling and contraction has been developed and modernized throughout history, with collaborations from eminent scientists such as René Descartes (1596 – 1650), Gottfried Wilhelm Leibniz (1646 – 1716), Henry De la Beche (1796-1855), Elie de Beaumont (1798-1874), Thomson William - Lord Kelvin (1824-1907), James Dana (1813-1895), and Eduard Suess (1831-1914).

In this context, Eduard Suess formulated one of the most critical concepts in stratigraphy, which deals with the cyclicity of global sea level. According to Suess (1888), the contraction of the planet produced eustatic movements. Such movements can be negative (decrease in global sea level) due to the subsidence of ocean basins, or positive (increase in global sea level) due to the continuous discharge of sediments that fill these basins. After Suess (1888), a tremendous scientific effort was initiated to understand the planet's internal dynamics, its relationships with the development of ocean basins and eustatic variations, and the potential to use the oscillations of the absolute sea level for global stratigraphic correlations.

In 1890, Grove Karl Gilbert (1834 – 1918) recommended using the term "diastrophism" to describe the vertical movements of the lithospheric crust. Gilbert (1890) proposed dividing dystrophic processes into orogenic processes, related to the relatively smaller scale that produced the mountain ranges, and epirogenic, related to the broader movements that form the boundaries of continents and oceans.

For many years later, the nature of diastrophism was up for debate in the scientific community. "Have diastrophic movements been in progress constantly, or at intervals only, with quiescent periods between? Are they perpetual or periodic?" (Chamberlin, 1909, p. 689). Defending the periodic conception of diastrophism, Thomas Chamberlin (1843 – 1928) proposed a model for eustasy very similar to Suess (1888), in which the isostatic balance would promote vertical adjustment cycles in the Earth's crust, leading to marine regressions and transgressions. The novelty offered by Chamberlin (1898) was the linkage between diastrophism, sea-level variations, and climatic cycles. In his theory, the weathering of the subaerially exposed continents during regression would promote substantial CO_2 consumption, causing global cooling. Conversely, during transgression, the excess of atmospheric CO_2 was supposed to improve warming by the greenhouse effect. Chamberlin's primary motivation was establishing a theoretical framework that could explain the global division of geological time and the stratigraphic correlations through base-level changes (Chamberlin, 1909). In his most famous work, *Diastrophism as the Ultimate Basis of Correlation*, Chamberlin (1909) reaffirms the global character of dystrophic movements and underlines their importance for correlations

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by base level. According to him, the synchronicity of these events, associated with variations in sea level, allows for transoceanic correlations.

During this same period, William Morris Davis (1850 – 1934) developed a geomorphic cycle theory to explain landform evolution. According to Davis (1899; 1922), after an initial and rapid tectonic uplift, landforms undergo weathering and erosion processes, evolving through several intermediate stages until culminating in a general peneplanization. A change in the erosion level caused by a new tectonic uplift would cause landform rejuvenation, starting a new geomorphic cycle. Although later criticized for not considering all the complexity of geomorphological processes, Davis's theory became paradigmatic until the mid-twentieth century. Its cyclical conception influenced ideas about periodic variations in the generation, supply, and preservation of sedimentary deposits.

Barrell (1917) pioneered the understanding of the cyclic behavior of erosion and accumulation processes. He was the first to propose a systematic link, at different orders, between base-level changes and the preservation of the stratigraphic record. A synthesis of his ideas is presented in the diagram in Figure 7. With the alternation between deposition and erosion, produced by the harmonic of long-term (diastrophic) and short-term (climatic) base-level fluctuations, Barrell illustrated that most of the geological time is contained in and represented by unconformity surfaces, which he called diastems. It is remarkable how many of the principles developed by this author are still in use. The sinusoidal representation of the base-level harmonic oscillations introduced a widespread way of illustrating the logic of stratigraphic evolution (e.g., Van Wagoner, 1990).

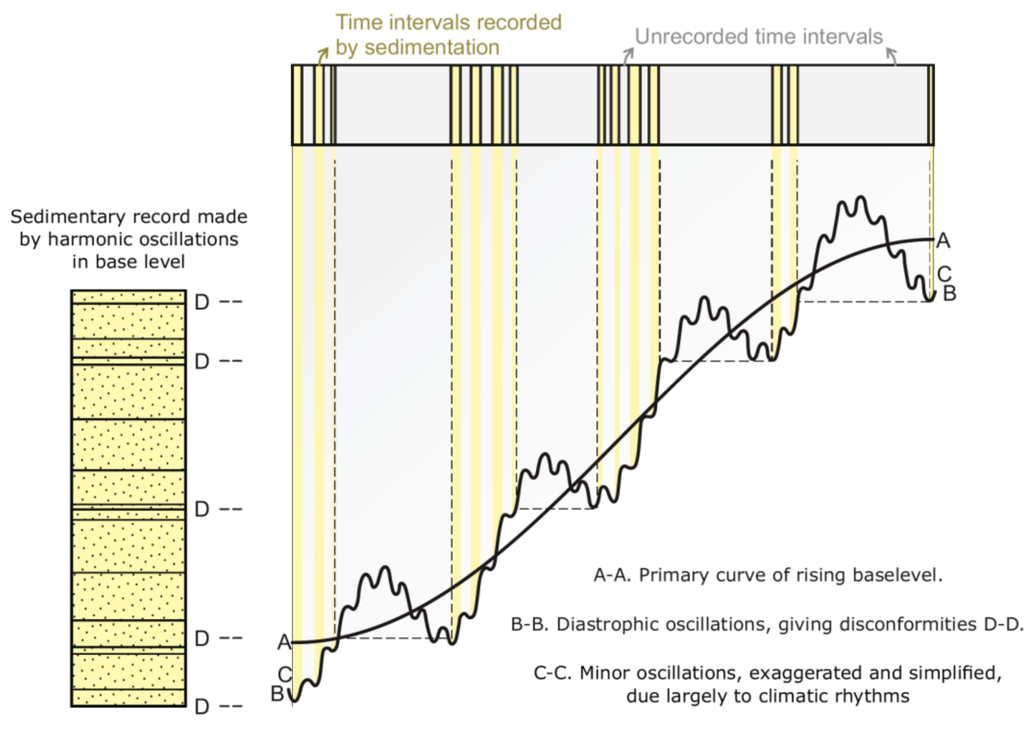

Figure 7. Cyclical variations of the base level and their control on preserving the stratigraphic record through an alternation of deposition and erosion (modified from Barrell, 1917).

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A year after the First World War, Alfred Wegener (1880 – 1930) published the first edition of *The Origin of the Continents and Oceans*. Wegener (1915) was not the first to postulate the lateral movement of continents. However, he deserves the central role in this theme above all for his persistence in defending continental drift against a scientific community hostile to these ideas. The exaggerated reactions to Wegener's theory are due, in part, to the fact that he did not have a satisfactory explanation for the mechanism controlling continental movements (Beckinsale and Chorley, 2003). Another understandable reason is the traditional resistance of the scientific community to theoretical innovations. The continental drift proposal completely contradicted all formulations in force at the time. Since the beginning of the 19th century, what was advocated in force until the 1960s were the large vertical movements of the Earth's crust, which reached a final formulation in the geosyncline theory (Gnibidenko and Shashkin, 1970).

Hans Stille (1876 – 1966) was one of the great geologists of the geosyncline theory. Dedicated to describing the evolution of various geological terrains, Stille (1924) mapped successive unconformities in marine deposits. He interpreted that orogenic processes occurred in global synchrony, producing regressions and transgressions of sea level. This proposal cannot be seen as fundamentally new, but Stille (1924) was a pioneer by drawing up the first eustatic variation curve for the Phanerozoic (Figure 8A).

Amadeus William Grabau (1870 – 1946), through detailed stratigraphic data and correlations in extensive areas of North America, Europe, and Asia, presented a proposal for sea-level fluctuations for long geological periods (Figure 8B). Although Stille's and Grabau's cyclic conceptions of sea-level variations are similar, Grabau questioned the synchronicity of orogenies in the entire world. He considered these processes to be of local importance and believed that simultaneous sea-level fluctuations could be related to changes in the volumes of ocean basins (Johnson, 1992). Grabau was inspired by the work of Alfred Wegener (Mazur, 2006), and he cited *The Origin of the Continents and Oceans* in his most significant publication, *The Rhythm of the Ages: Earth History in the Light of the Pulsation and Polar Control Theories*, published in 1940 (Johnson, 1992).

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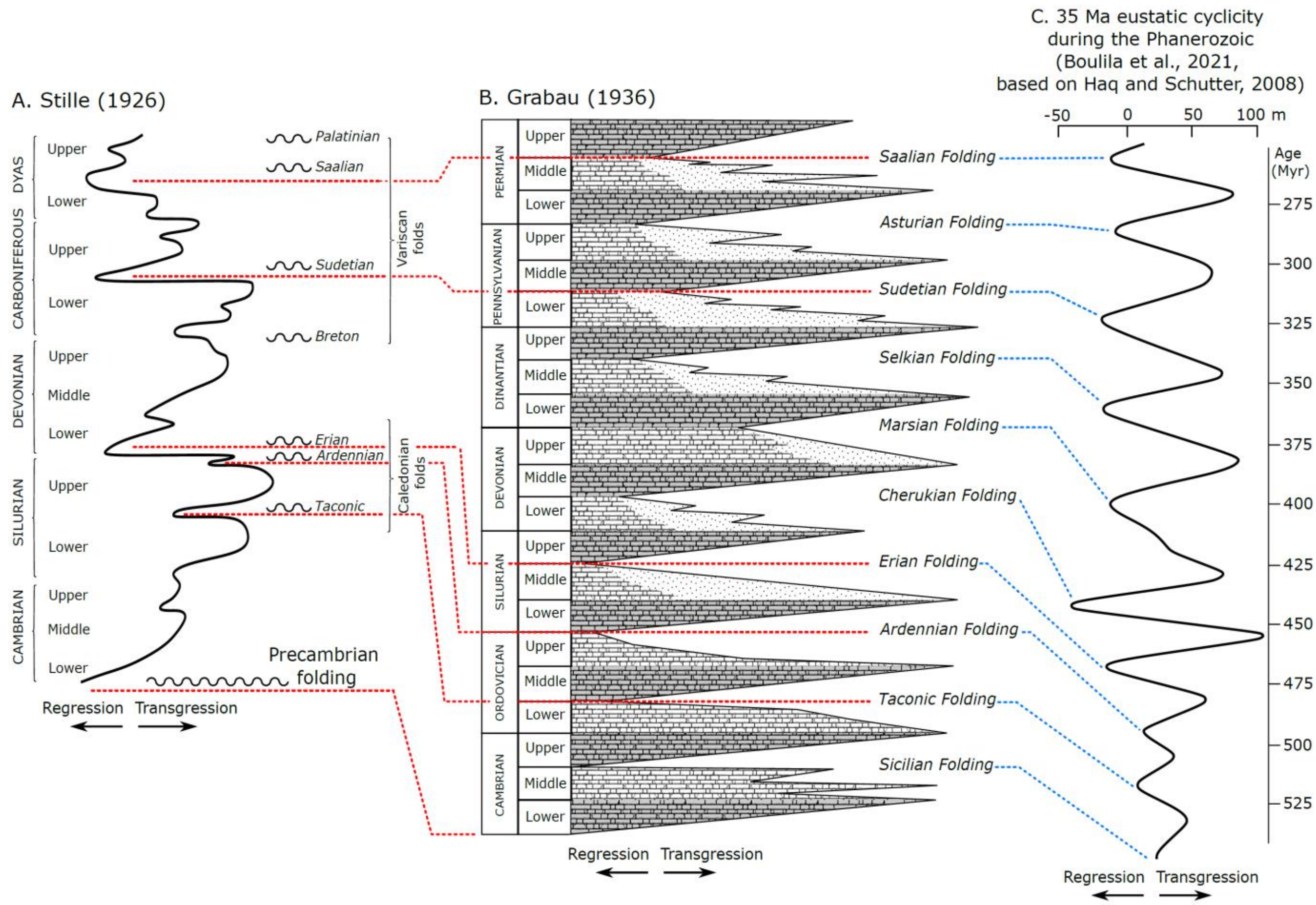

Figure 8. Global sea-level curves: A. Modified from Stille (1926) and B. modified from Grabau (1936). Both indicate the main orogenetic periods associated with rapid marine regressions. The red lines indicate the same events identified by Stille (1926) and Grabau (1936). C. Paleozoic eustatic cycles of approximately 35 Myr (determined by bandpass filtering of data presented by Haq and Schutter, 2008) and potential correlation (blue lines) with equivalent cycles of Grabau (1936) (modified from Boulila et al., 2021).

2.2.2 Plate Tectonics and Wilson Cycles

Scientific progress and field evidence, particularly concerning the origin of mountain belts, have resulted in the questioning of the contraction theory (e.g., Dutton, 1874), which was finally abandoned. A crisis in the field of tectonics was provoked by the discovery of radiometric dating, which challenged the Earth's long-term cooling, and by the Alpine nappes and thrust sheets that demonstrated the mechanisms of large horizontal displacements of the crust. This crisis did not end until the definition of plate tectonics in the 1960s (O'Hara, 2018).

During the 1960s, advances in post-World War II oceanographic research provided evidence for the evolution of the ocean floor. Such discoveries explained Alfred Wegener's theory of continental drift (Keary et al., 2009), and the roots of the future plate tectonic paradigm were established (Le Pichon, 2019). The development of this theory can be considered the most

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significant advance in understanding the Earth's dynamics and has been influencing even the study of other planets (e.g., Hawkesworth and Brown, 2018; Karato and Barbot, 2018; Duarte et al., 2021).

John Tuzo Wilson (1908 – 1993) was one of the leading geoscientists developing the theory of plate tectonics. Wilson (1965) was the first to mention the existence of large rigid plates, describing specific limits of these, which the author called transform faults. However, Wilson's most emblematic work was published the following year. Wilson (1966) presented a specific aspect of the geotectonic process, showing the oceans' successive opening and closing (Figure 9). Today, the so-called Wilson cycle describes the periodicity with which large continental masses separated and came back together. Over the past 50 years, this concept has proven to be crucial for the theory and practice of geology (Wilson et al., 2019).

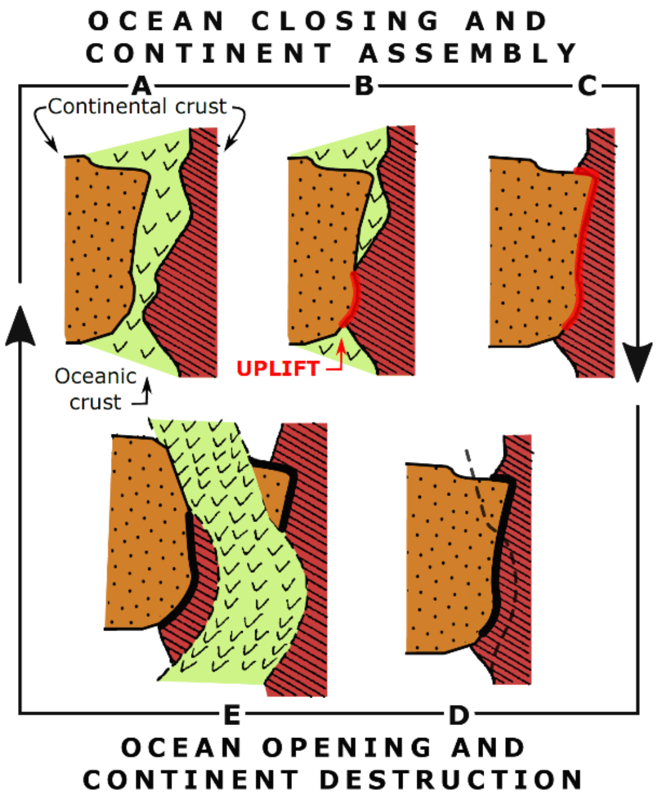

Figure 9. Ocean closing and opening cycle (modified from Wilson, 1966): A - A closing ocean; B - First contact between two opposite continental coasts; C - Ocean closure and final collision of opposite continental coasts; D - A hypothetical line (dashed) along which a new continental rupture would engender a younger ocean to re-open; E - A new ocean opening after the break-up of an old continent.

It is notorious how the theory of plate tectonics followed the stubborn uniformitarianism of processes advocated by James Hutton and Charles Lyell. Stern and Scholl (2010) related the tectonic processes to cycles of creation and destruction of the continental crust, defining a particular equilibrium on Earth. They encapsulated this equilibrium in the traditional Chinese

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concept of yin-yang, whereby dualities work together and in opposition. About this maintenance of geological systems defined by plate tectonics, Schwarzacher (2000, p.51) wrote:

> *The environments of deposition from the Precambrian onwards have been similar and repeat themselves; apart from the fortunate exception of the biosphere, there are very few indications of a progressive development in geological processes during the last 1000 Ma. Indeed, based on our present observations, one could easily believe that most sedimentation and therefore stratigraphy should have ended long ago. All basins should have been filled and all mountains eroded. This is not the case and leads us to believe that tectonic events must interfere and revitalize the sedimentation systems.*

The Wilson cycle was vital to define the assembly and the breaking up of supercontinents. This self-organization in plate tectonics has been studied for decades, whose periodicity is in the range of 300-800 million years (Mitchell et al., 2021). Hence, new hypotheses for global cycles could also be formulated, and several questions about the impacts of tectonic events on sea-level and climatic variations were answered. For example, based on the Wilson cycles, Fischer (1981, 1982) formulated the climatic oscillation produced by Earth's icehouse and greenhouse states (Figure 10).

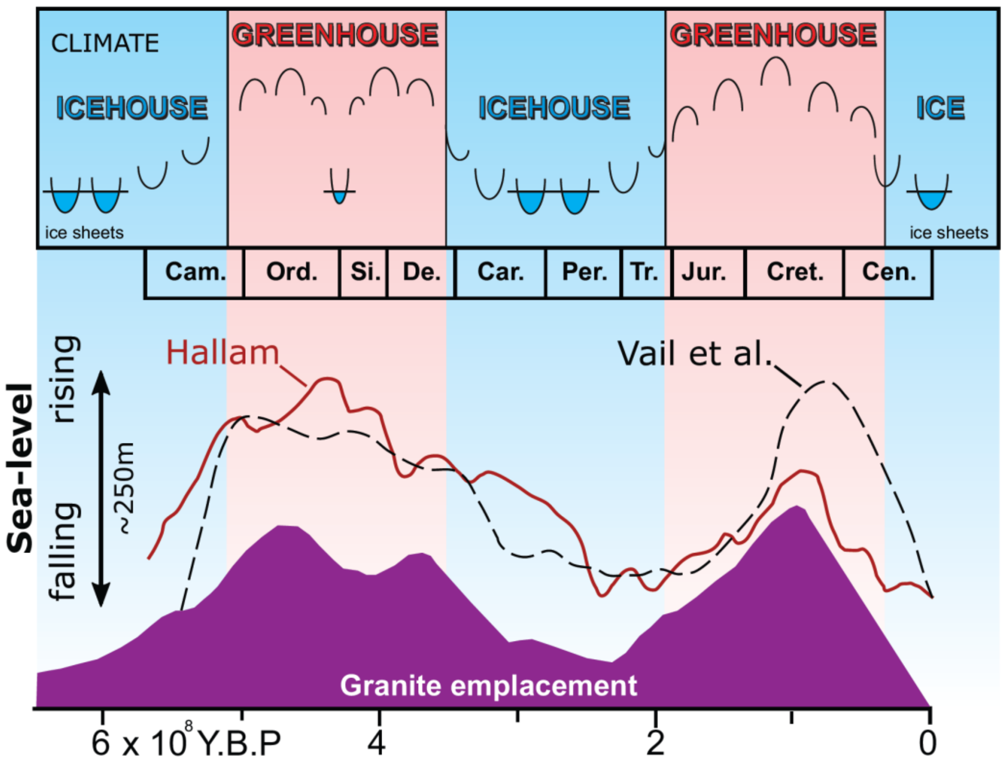

Figure 10. Cyclic outlines of Phanerozoic history (modified from Fischer, 1981;1982). Climatic oscillations are composed of greenhouse and icehouse states, with minor internal climatic fluctuations. Sea-level curves, according to Vail et al. (1977) and Hallam (1977). Global granite emplacement was deduced from data based on the American granite emplacements (after Engel and Engel, 1964).

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2.2.3 Internal Geodynamic Forcings in the Earth System

Currently, the periodicity of several processes in the Earth's internal dynamics is well known (e.g., Matenco and Haq, 2020; Figure 11). Mitchell et al. (2019) conducted time-series analyses of hafnium isotopes in zircon (Hf-zircon) to identify statistically significant periodicities of magmatic systems throughout geological time. The Hf-zircon analyzed by LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) represents a well-dated proxy for the evolution of magmatism related to tectonic and mantle convection cycles. From time-series analysis of the global Hf-zircon database for the last ~ 2 Gyr, the authors defined a hierarchy of geodynamic cycles (Figure 12), analogous to the orbital ones (Figure 2).

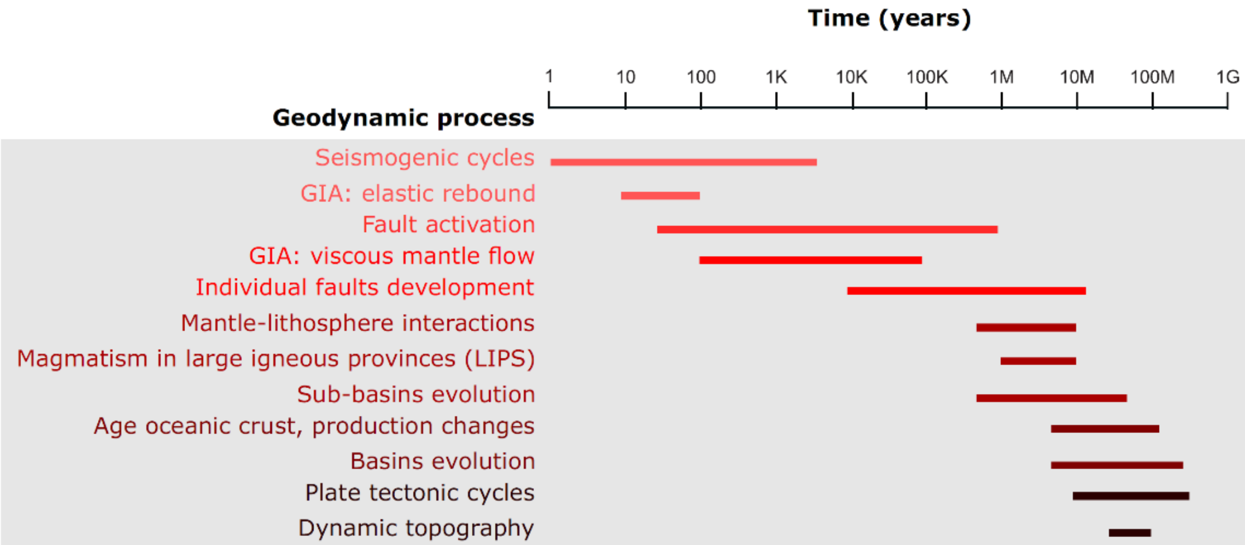

Figure 11. Temporal variability of the main periodic geodynamic mechanisms (based on Matenco and Haq, 2020).

Mitchell et al. (2019) recognized the periodicity of the superocean cycle (~1.2 Gyr), the supercontinent cycle (~600 Myr), the Wilson cycle (~275 Myr), and an upper mantle cycle (~60–80 Myr). These cycles appear to be harmonics, implying a coupling between the mantle and lithosphere convections. In addition to these, magmatic cycles of ~20 Myr and ~6 Myr are suggested by the high-resolution circum-Pacific records. According to these authors, "the hierarchy of geodynamic cycles identified with Hf isotopes of zircon appears to represent, according to bandwidth, the last frontier of cyclicity in the Earth system to be identified and explored" (Mitchell et al., 2019, p. 247).

Climatic and eustatic oscillations may have interacted with internal geodynamic processes as triggers or feedbacks (e.g., greenhouse-icehouse cycles; Figure 10). Changes in ocean circulation related to the configuration of the continents and global volcanic pulses are an example of a potential influence on Earth's climate (Rampino et al., 2021). The link between Earth's internal dynamics and eustasy may come from changes in the volume of marine waters (water exchange with a mantle) and in the volume available in ocean basins (ocean ridge volume; dynamic topography; seafloor volcanism; continental collision), which operates on the long term (greater than 1 Myr; e.g., Sames et al., 2016; 2020; Figure 13)

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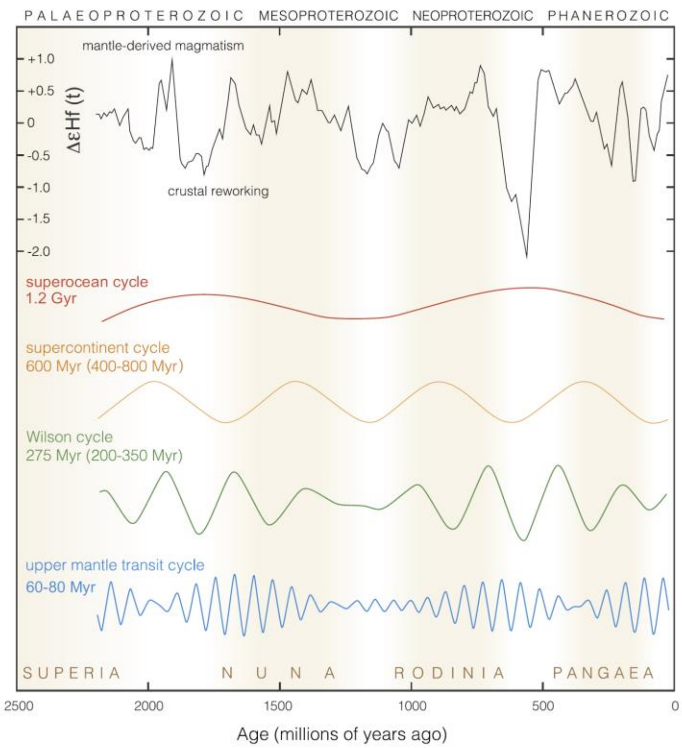

Figure 12. Global Hf database (black) and cycles determined by the time-series analysis: superocean cycle (~1.2 Gyr; red), the supercontinent cycle (~600 Myr; yellow), the Wilson cycle (~275 Myr; green), and an upper mantle cycle (~60–80 Myr; blue).

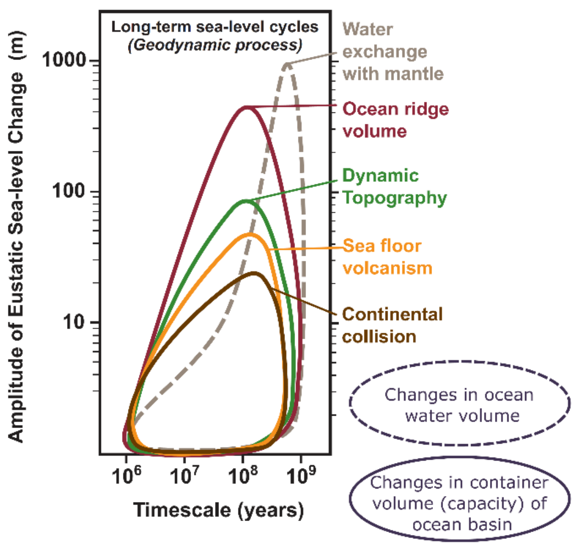

Figure 13. Log-scale diagram of the timing and amplitudes of the main mechanisms that control "long-term" sea-level variations related to internal geodynamic processes. The values represented must be considered as average (modified from Sames et al. 2016).

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Disagreements about the global synchronicity of tectonic cycles have been raised since the beginning of the 20th century. According to Willis (1910, p. 247), "each region has experienced an individual history of diastrophism, in which the law of periodicity is expressed in cycles of movement and quiescence peculiar to that region". This idea was encapsulated in the concept of relative sea-level change (e.g., Wilgus et al., 1988). Relative sea-level change (as opposed to eustatic sea-level change) is caused by tectonic deformation of the crust in marine and coastal areas, which results in uplift and subsidence of the land relative to the sea surface. Generally, these processes have a local to a regional extent and occur at a higher frequency than global geodynamic processes (e.g., Matenco and Haq, 2020; Figure 11). Thus, sea-level changes caused by geodynamic processes can be local when such processes are also localized (e.g., bradyseism; Figure 4).

The cyclical behavior of the mantle and the lithosphere, in association with astronomical cycles, completes the puzzle of cyclicity in the Earth system. The connection between the Earth's internal and external systems is not adequately investigated because tectonic and astronomical influences are often considered independently. Boulia et al. (2021) suggest a potential coupling between Milankovitch forcing and Earth's internal processes for the eustatic sea-level record in the 35 Myr cycle range during the Phanerozoic. This is a cyclicity that is compatible with the one that was recognized a long time ago, by several authors, such as Stille (1926) and Grabau (1936) (Figure 8C). A challenge for stratigraphy is understanding how the Earth system's conduction mechanisms are imprinted in the geological record. As Barrell (1917) concluded, "sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on stone tablets, of these increasing waves of change that pulsed through geological time." Such "waves" may correspond to the causal mechanism of biological extinctions, comet impacts, orogenic events, oceanic anoxic events, and sea-level changes, which support the division of geological time into intervals for global correlations (e.g., Rampino et al., 2021; Boulia et al., 2021).

3 Cyclicity of Stratigraphic Record

> *The idea of a cycle involves repetition because a cycle can be recognized only if units are repeated in the same order. The question that inevitably arises is: How closely similar must the repetition be? An answer seems to depend on two requirements: (1) nearly complete transitions between variants must be observed, and (2) a generalization must be made reducing the cycle to its simplest form by excluding all unessential details. The cycles, then, must be closely similar with respect to this simple form (Weller, 1964, p. 613).*

According to Goldhammer (1978), most, if not all, stratigraphic successions exhibit repetitions of strata at different scales. Throughout the history of stratigraphy, the concept of cyclicity played a crucial role in the inductive observations of the record and subsequent deductive reasoning. Several approaches have been used to describe this cyclicity. Among them, the following lines of description and interpretation will be briefly presented: sedimentary facies cycles, cyclothems, clinoforms, stratigraphic sequences, and astrocycles.

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3.1 Sedimentary Facies Cycles

Sedimentary cycles are recurrent sequences of strata each consisting of several similar lithologically distinctive members arranged in the same order. A great variety of cycles is possible ranging from simple to quite complex but only a comparatively few types actually have been recognized. Cycles may be either symmetrical or asymmetrical depending upon the pattern presented by their members. They record the occurrence of definite series of physical conditions, and resulting sedimentary environments, that were repeated in the same order with only minor variations (Weller, 1960, p. 367).

During the 15th and 16th centuries, observing the landscape and the natural phenomena that modify it played a crucial role in constructing modern science, especially in Earth sciences (Puche-Riart, 2005). For example, through detailed observations of successive rock strata, Leonardo da Vinci (1452-1519) expressed nature in his paintings (Ferretti et al., 2020). He was probably one of the first to understand erosion, transport, deposition, and lithification processes from field observations. In "Codex Leicester", Leonardo da Vinci shows the vertical and the lateral organization of rocky beds observed in the Alps that he interpreted as a record of river flood cycles (Ferretti et al., 2020).

In 1669, Nicolaus Steno (1638-1686) published one of the most crucial works about the genesis of rock layers and their fossil components. Based on an interpretation of the geological evolution of Tuscany, he proposed three fundamental stratigraphic principles that continue to be used today (Kravitz, 2014). Through an evolutionary diagram (Figure 14), Steno suggested that the sedimentary beds are formed by successive floods, followed by reworking that erode and deform them. He noted that sediment layers were deposited in chronologic successions that display the oldest layers on the bottom and the youngest ones on top of the pile (principle of superposition). According to him, initially, the strata are organized in a set of horizontal layers (principle of original horizontality) that could be later eroded and deformed, and new horizontal layers are deposited over them. Concerning the strata's geometry, Steno defined that each sedimentary bed extended laterally in all directions (principle of lateral continuity) until it reached an obstacle, such as the basin's border.

Nicolaus Steno was responsible for introducing the term "facies" into the geological literature. He used it to describe the fundamental characteristics of a part of the Earth's surface during a specific geological time (Teichert, 1958). Later, this concept evolved through the descriptions of Amanz Gressly (1814 – 1865) in the Jura mountains at the French-Swiss border. Gressly (1838) defined the sedimentary facies as the different lithological features and fossil components of a sedimentary layer, interpreted as a record of the original depositional processes. He explained the genesis of sedimentary facies as the product of processes that operated in depositional environments and demonstrated, through stratigraphic correlations, the lateral facies transitions that compose a mosaic of environments along a depositional profile (Cross, 1997).

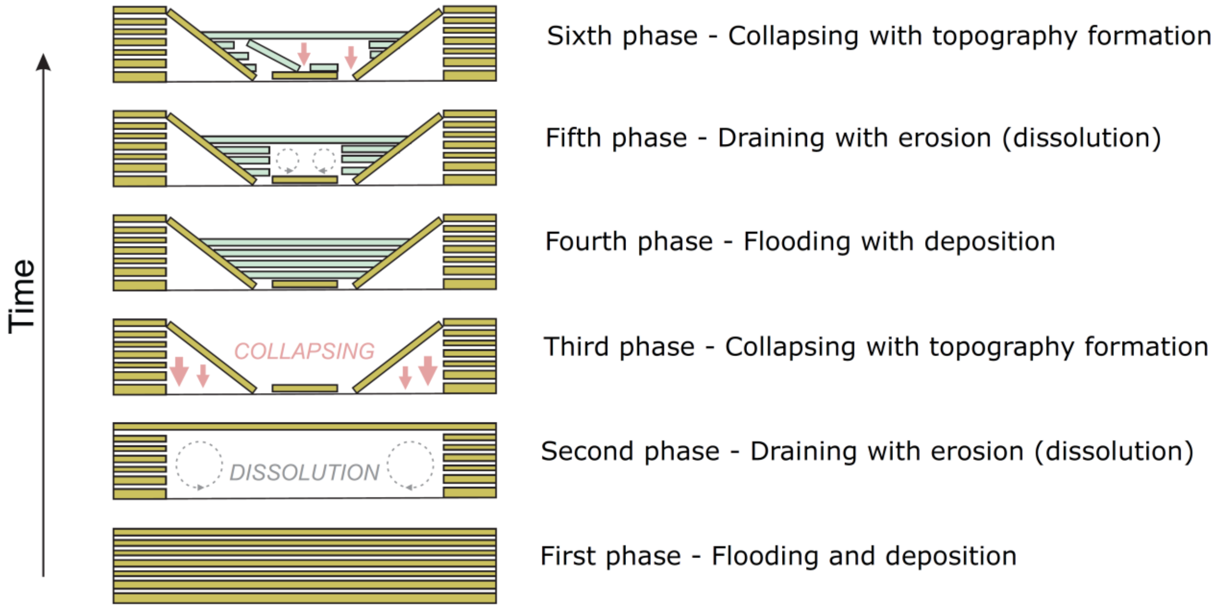

Figure 14. Steno's evolutionary diagram describes six stages for the geologic history of Tuscany, including flooding cycles and crustal collapse (modified from Kravitz, 2014).

In 1894, Johannes Walther (1860 – 1937) introduced an essential geological principle associated with the concept of facies (Middleton, 1973). Known as "Walther's law of facies", this principle states that any vertical facies succession is a record of depositional environments that were laterally adjacent to each other in the geological past. This vertical and lateral facies correspondence is still used today for paleogeographic reconstructions.

Between the 19th and 20th centuries, several works presented detailed sections demonstrating repeated associations of different types of rocks (Weller, 1964). The economic interest in Carboniferous coal beds fueled some of the earliest observations. In 1912, Johan August Udden (1859 – 1932) was a pioneer in recognizing cycles in the stratigraphic record. In a report about the geology of the U.S. state of Illinois, he identified facies cycles in Pennsylvanian strata, composed, from bottom to top, by layers of coal, limestone, and sandstone (Figure 15). Udden (1912) interpreted such cycles as products of successive transgressions and regressions of the shoreline during the basin's subsidence. He established that stratigraphic surfaces marked by paleosols correspond to the end of each cycle. According to him, these surfaces represent depositional gaps.

Laboratory simulations were introduced during the 1950s and 1960s, culminating in the flow regime concept (Simon and Richardson, 1966). This advance improved the interpretation of sedimentary structures preserved in the geological record (e.g., Allen, 1963; Middleton, 1965). Concomitantly, there was also much progress in facies models through studies of modern sedimentary environments (e.g., Fisk et al., 1954; Illing, 1954; Oomkens and Terwindt, 1960; Bernard and Major, 1963; Shearman, 1966; Glennie, 1970). During this period, specialists began to divide themselves between sedimentologists and stratigraphers (Middleton, 2003).

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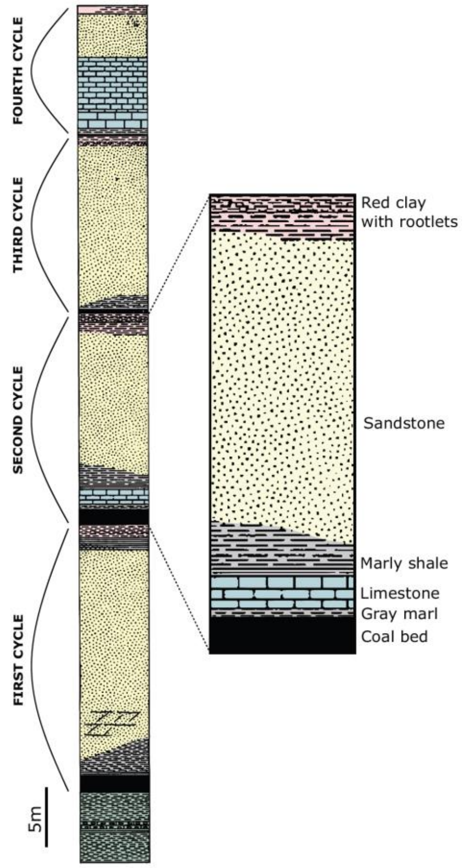

Figure 15. Cycles in the Pennsylvanian of Illinois, United States (modified from Udden,1912).

In the 1960s, the stratigraphic application of facies models evolved considerably through the analysis of cyclicity seen in the outcrops (e.g., Weller, 1960). Recurrent sequences of sedimentary facies, arranged in a specific order, have been interpreted as the record of similar depositional and environmental processes, repeated at all scales, from millimeters to many hundreds of meters (Goldhammer, 1978; Schwarzacher, 2000). In this context, specific terms were created for describing sedimentary facies with regular alternation, such as "cyclites" or "rhythmites" (e.g., Kvale, 1978; Brodzikowski and Van Loon, 1991). Although generic, these terms have been closely associated with regular climate cycles (e.g., Chandler and Evans, 2021) or those produced in tidal environments (e.g., Kvale, 1978).

Researching cyclic depositional mechanisms in alluvial plains, Beerbower (1964) defined the concepts of autocyclic versus allocyclic. Autocyclic was defined as the sedimentation record generated purely within the given sedimentary system by the distribution of energy and sediments, such as lateral channel migration and meander abandonment. On the other hand, allocyclic was associated with the external processes that cause changes in the alluvial channels' discharge, loading, and inclination. They differ from autocyclic alternations in their wider lateral extension along the basin or even to other depositional basins.

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With some modernizations, the concepts of autocyclic and allocyclic controls currently encompass all geochemical, ecological, and physical sedimentary processes (Cecil, 2003). Nowadays, autocyclic dynamics are understood as the spontaneous form of deposition within sedimentary systems, determining spatial and temporal heterogeneities in the way sediments and water are distributed in a landscape (Hajek and Straub, 2017; Figure 16). Delta switching and lateral migration of channels, dunes, or ripples are examples of autocyclic processes that produce cyclical deposits (e.g., Hajek and Straub, 2017; Miall, 2015). Other examples include episodic events, which, although recurrent, do not have periodicity, such as storms and sediment gravity flows (e.g., Einsele, 2000). The autocyclic dynamics must be self-regulating and include feedback mechanisms to produce cyclic sedimentary records (Goldhammer, 1978). Since they do not always have a periodic regularity, the preference is to use the term "autogenic" (Miall, 2016).

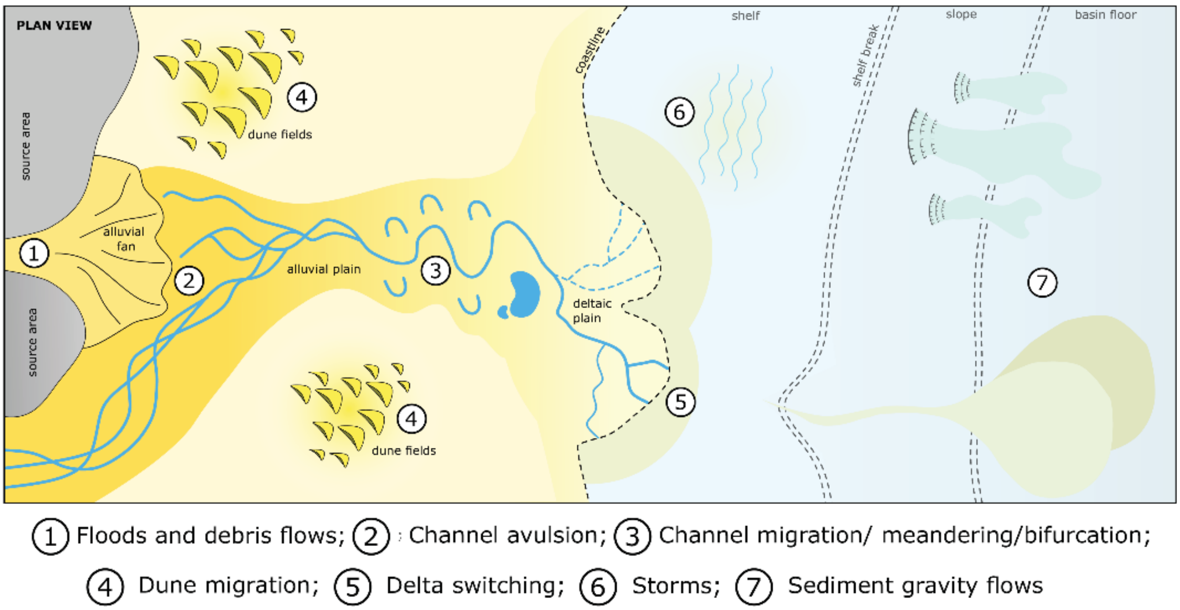

Figure 16. Schematic illustration with some autogenic controls on sedimentation in different environments.

In turn, allocyclic (or allogenic) controls correspond to regional or global processes fundamentally related to climate, eustasy, and tectonics. These processes influence, at different magnitudes and frequencies, the production, transport, accumulation, and preservation of sediments, be they inorganic or organic, clastic, or chemical (e.g., Strasser et al., 2006; Holbrook and Miall, 2020; Matenco and Haq, 2020; Figure 17). In contrast to autocycles, the allocyclic controls are regular and tend to have known frequencies (as seen in section 2). They also define accommodation (defined by eustatic sea level and subsidence) and make the link to sequence stratigraphy (e.g., Holbrook and Miall, 2020; Fragoso et al., 2021). Hilgen et al. (2004) advised that even the record produced by sudden autocyclic events (e.g., storms) may occur in clusters related to allocyclic controls (e.g., astronomical). Furthermore, the understanding of the organization of fluvial systems, mainly controlled by the autogenic dynamics, was discussed by Abel et al. (2013). According to these authors, the regularities in such systems could be linked to allogeneic, astronomically forced climatic changes.

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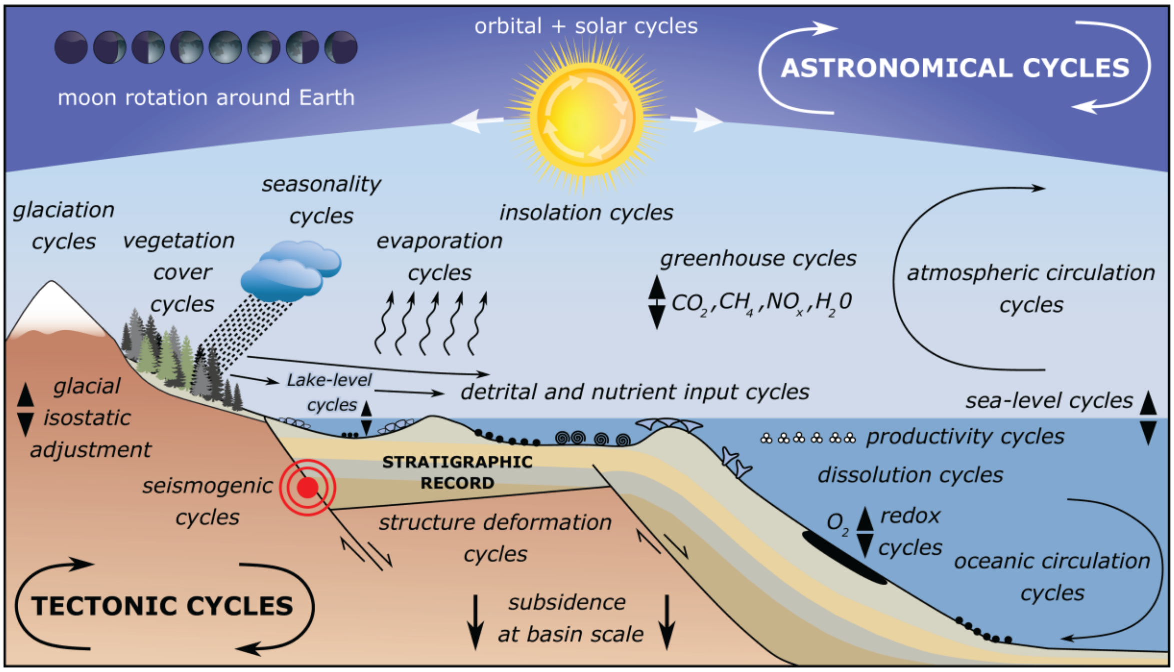

Figure 17. Schematic diagram illustrating the main allocyclic controls on sedimentation (modified from Strasser et al., 2006).

3.2 Cyclothems

Between the 1930s and 1960s, the sections presented by Udden (1912) became emblematic. Initially called "suites" (Wanless, 1929) or "cyclical formations" (Weller, 1930, Wanless, 1931), it was the term "cyclothems" (Wanless and Weller, 1932) that triumphed in the literature for describing such cyclic facies alternations.

The concept of cyclothems has become familiar to most geoscientists who describe sedimentary facies repetitions (e.g., Weller, 1943). The progress of the work in the Pennsylvanian of Illinois revealed that the recurrence of individual cyclothems does not only correspond to the unique rhythms to be observed in stratigraphic successions but is also part of a larger order.

> *This repeated succession of cyclothems of different character indicates a rhythm of larger order than that shown in the individual cycles and suggests the desirability of a term to designate a combination of related cyclothems. The word "megacyclothem" will be used in this sense to define a cycle of cyclothems (Moore et al., 1936, p. 29).*

According to James Marvin Weller (1899 – 1976), "these larger rhythms may be the long-sought key that will solve some of the perplexing problems of interbasin correlation" (Weller, 1943, p. 3). This author later proposed the existence of even larger groups, called hypercyclothems (Weller, 1958). This marked characteristic of the cyclicity in the sedimentary record, in which individual cycles occur in clusters that make up larger cyclical units, remains in modern approaches of sequence stratigraphy (Catuneanu, 2019a; 2019b; Magalhães et al., 2020; Fragoso et al., 2021; see item 3.3) and cyclostratigraphy (e.g., Hinnov, 2018; see item 3.4) The term "stacking pattern" is often used to describe a hierarchical order of cyclical units.

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Raymond Cecil Moore (1892 - 1974) presented another feature of the cyclical stratigraphic record quite pertinent in the modern context of sequence stratigraphy, concerning the definition of boundary surfaces. According to Moore (1964), both cyclothems and megacyclothems are limited by key surfaces, marked by disconformities or a change from continental to marine sedimentation (Figure 18).

Concerning the origin of cyclothems, Klein and Willard (1989) argued that such units are the product of the combined action of tectonic and eustatic processes. According to these authors, the integrated analysis of parameters related to geotectonic evolution, global paleoclimate (controlled by orbital, Milankovitch cycles), and laterally changing regional subsidence allows understanding the paleogeographic variations that gave rise to marine and continental cyclothems, along with lateral correlations (Figure 19). This approach presents many parallels to the analysis of systems tracts in the context of sequence stratigraphy (e.g., Posamentier et al. 1988; Hunt and Tucker 1992; Posamentier and Allen 1999).

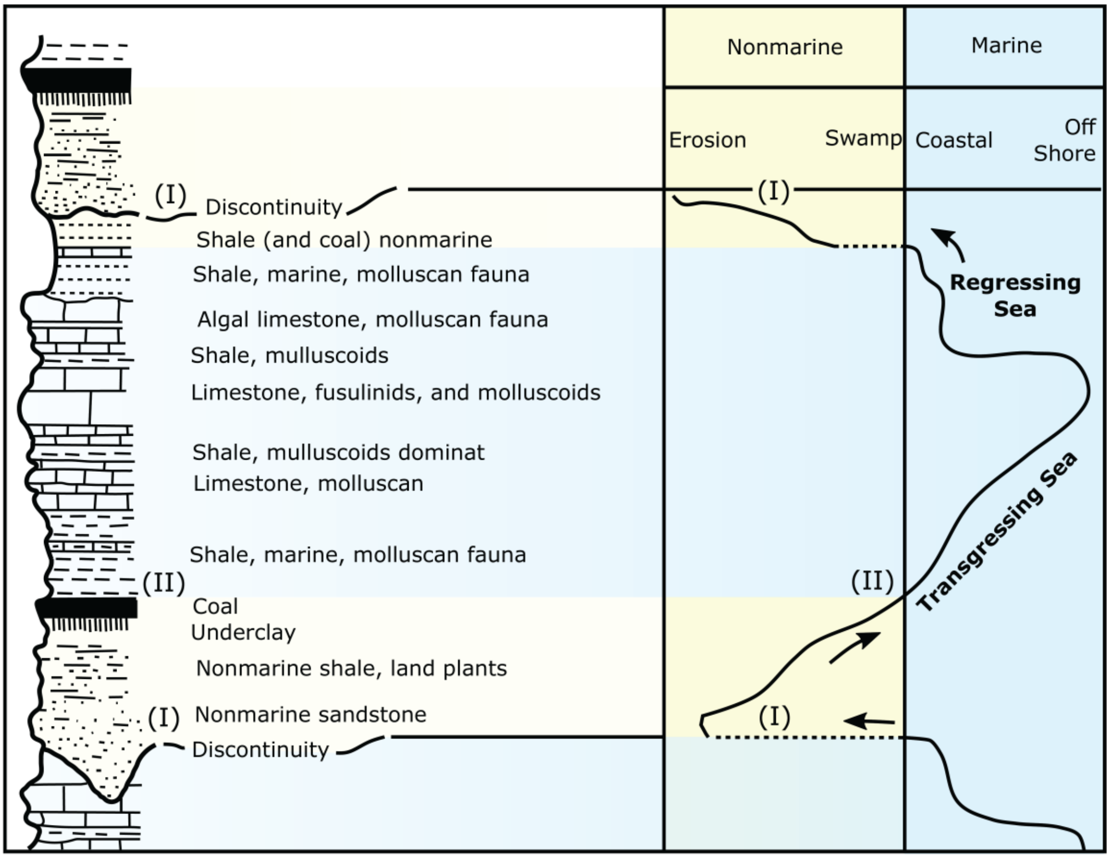

Figure 18. Representative section of cyclothems indicating the alternation of continental and marine paleoenvironments (modified from Moore, 1964). The alternatives of limits for cyclothems are: (I) disconformities. (II) the transition from non-marine to marine conditions.

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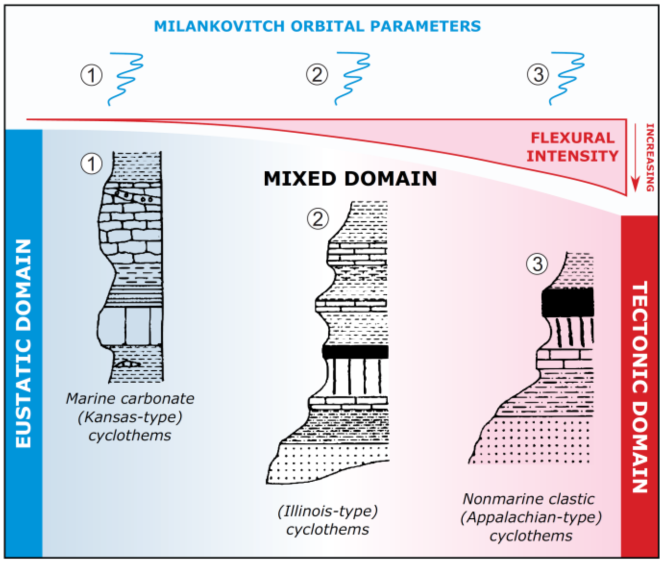

Figure 19. The genesis of the different types of cyclothems in North America related to orbital parameters and lateral differences in the crust's flexural intensity (modified from Klein and Willard, 1989).

3.3 Clinoforms

A broader analysis of the geometry of sedimentary deposits also revealed sedimentological alternations, which contributed to the definition of cyclic stratigraphic units. John Lyon Rich (1884 – 1956) was the first to describe the inclined geometry of marine deposition. Rich (1951) defined that, along a transect from coast to basin, the sedimentary deposits can be subdivided into three depositional forms: undaform, clinoform, and fondoform (Figure 20). Among these terms, only "clinoform" is being used nowadays. However, the theoretical basis brought by such an approach remains similar, especially regarding the possibility of shifts between these environments caused by sea-level changes (Figure 20B), resulting in characteristic successions of the geometry of strata (Figure 20C).

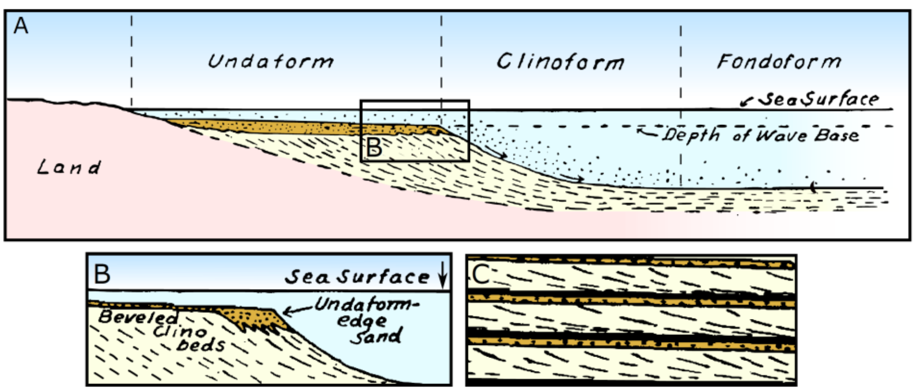

Figure 20. Sketches and terminology for coastal marine deposits (modified from Rich, 1951): A) Undaform, clinoform, fondoform; B) Area of thick sand on the outer edge produced by the slight reduction in sea level; C) Alternations of coastal marine deposits produced by intermittent changes in sea level.

DeWitt Clinton Van Siclen (1918 – 2001) considered the sloping geometries of continental margin deposits to describe the lateral variations observed in the cyclothems. According to Van Siclen (1958), the alternation of fluvial and coastal deposition with erosional disconformities predominates landward, grading basinward to alternating marine and terrigenous deposition, and finally reaching a totally marine domain, with an alternation of clastic and carbonate deposits. The author described cycles in the deep sea composed of clastic sedimentation during stable or lowered sea level, and non-deposition or thin black-shale layers deposited during higher sea stands. Considering different scenarios of changes in sea level and sediment supply, Van Siclen (1958) proposed distinct types of clinoform successions (Figure 21). This approach was handy for correlating well data when seismics did not support the oil and gas industry. It is interesting to realize how such a concept is similar to the current sequence-stratigraphic models.

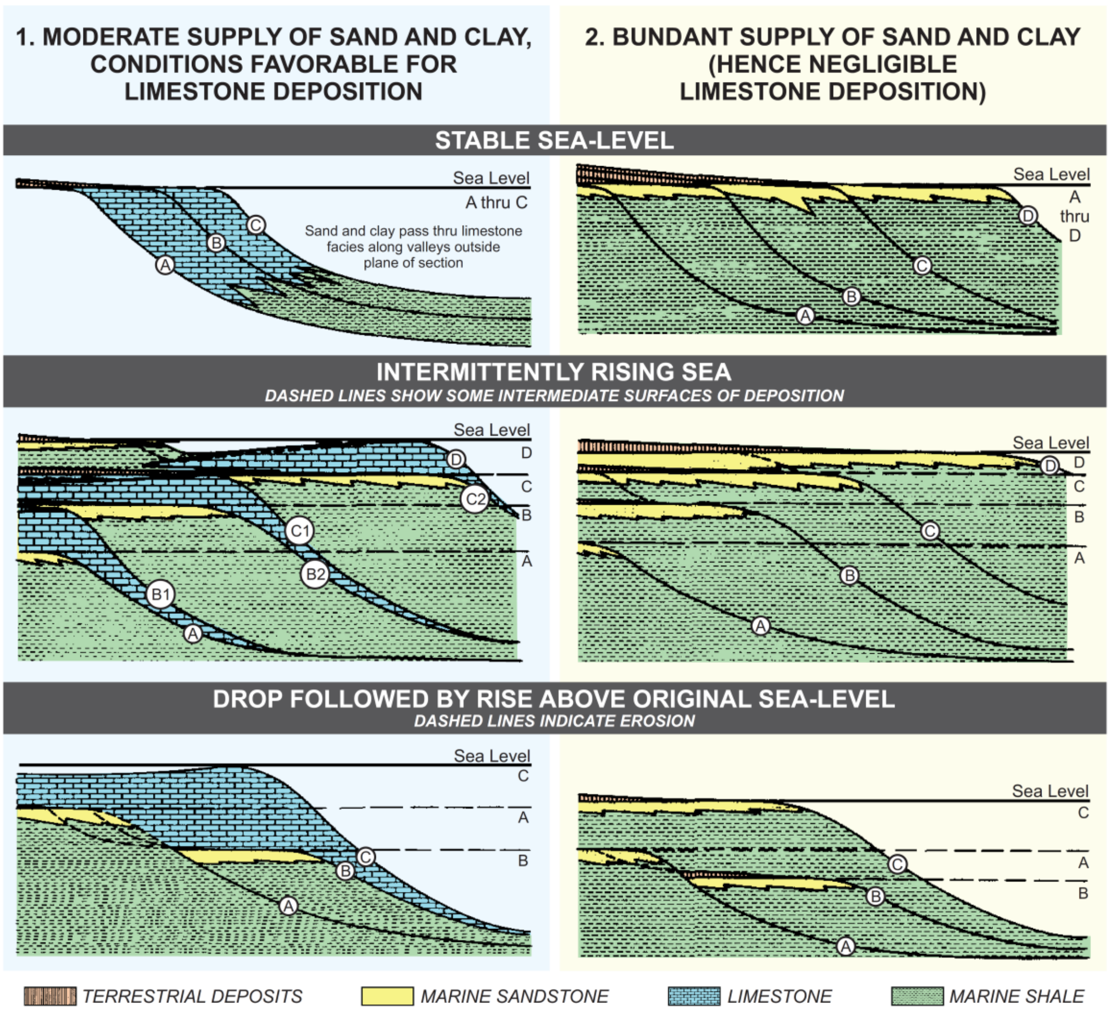

Figure 21. Different scenarios where sea-level changes and sediment supply cause different geometries and lithological compositions in continental margin deposition (modified from Van Siclen, 1958).

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3.3 Stratigraphic Sequences

> *Stratigraphic cyclicity can be observed at different scales. At each scale of observation (i.e., hierarchical level), the building blocks of the sequence stratigraphic framework are represented by sequences and their component systems tracts and depositional systems (Catuneanu, 2019b, p. 128).*

Laurence Louis Sloss (1913 – 1996) is widely recognized as one of the pioneers of the concept of sequence stratigraphy, and many credit him with instigating a revolution in stratigraphic thinking (Dott, 2014). Sloss et al. (1949) used for the first time the term "sequence" to refer to stratigraphic units that could be correlated over large areas through geological mapping and well data. Subsequently, this sequence model defined successive stratigraphic units bounded by "interregional unconformities" that covered the North American craton (Sloss, 1963; Figure 22).

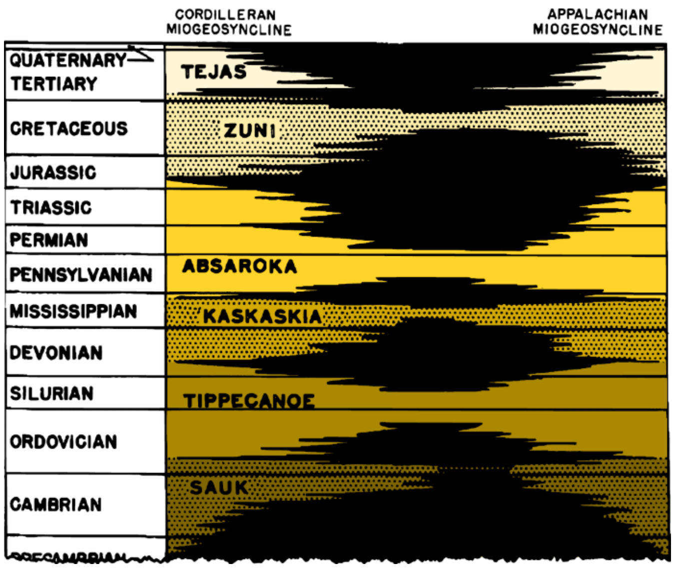

Figure 22. Sequences of the North American craton (modified from Sloss, 1963). The black areas represent temporal gaps, and the light areas represent the depositional units.

In the late 1960s, under Sloss' guidance, Peter Vail, Robert Mitchum, and John Sangree studied North American Pennsylvanian cyclothems (Dott, 2014). Similar to small-scale versions of Sloss sequences, bounded by numerous widespread unconformities, these cyclothems were interpreted by them as the stratigraphic record of glacioeustatic fluctuations. Subsequently, these three geologists collaborated with the Exxon research group to develop the method of interpreting seismic data, refining their mentor's concept of sequence (e.g., Mitchum, 1977).

During the 1960s and 1970s, the evolution of seismic interpretation was responsible for reuniting many stratigraphic concepts that underlie the current sequence-stratigraphic methodology. The first reference to the term "seismic stratigraphy" was published at the 27th Brazilian Congress of Geology (Fisher et al., 1973), and efforts in this area gained prominence in the international community through the AAPG Memoir 26 (Payton, 1977), where the main techniques developed by the Exxon research group were presented. The great innovation was to consider the continuous reflectors observed in seismic sections as

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depositional timelines. In this way, it became possible to interpret that surfaces representing an unconformity pass laterally to a correlative conformity, which was fundamental for the definition of a sequence (e.g., Mitchum, 1977). The seismic interpretation, together with biostratigraphic constraints, made it possible to establish chronostratigraphic correlations within a basin and between different basins (e.g., Mitchum and Vail, 1977; Figure 23). According to Vail (1992), this approach aimed at providing a unifying concept for sedimentary geology equal to what plate tectonics had done for structural geology.

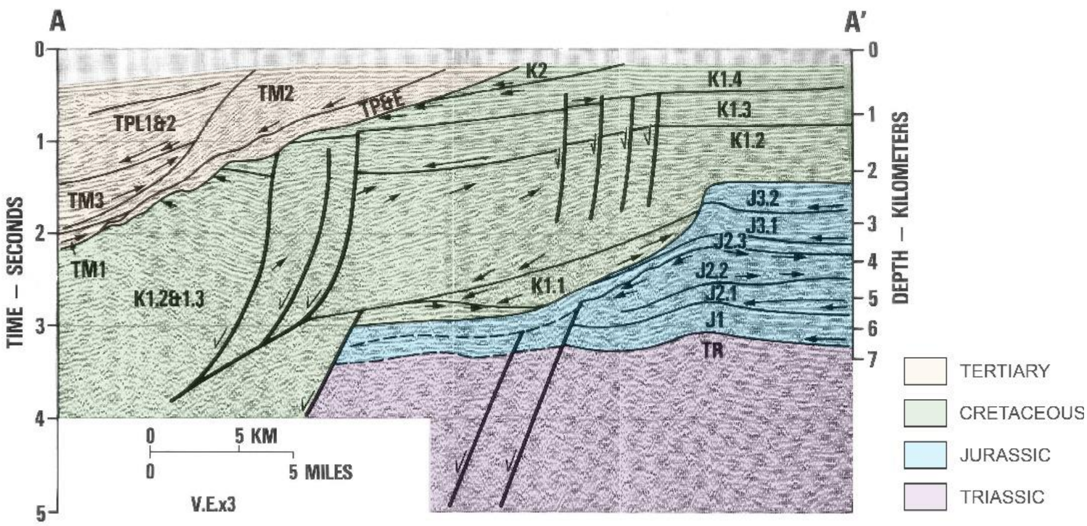

Figure 23. Seismic section from offshore northwest Africa showing sequences defined by seismic reflectors. Black lines show the sequence boundaries (modified from Mitchum and Vial, 1977).

Different sequence-stratigraphic models were presented between the 1970s and 1990s, resulting in a profusion of concepts and jargons. Catuneanu (2006) offered a complete review of these proposals. After the 2000s, a scientific effort was made to standardize the nomenclature and the methodology of sequence stratigraphy (Catuneanu et al., 2011), defining a simple and integrating workflow appropriate for modern stratigraphic analysis (Miall, 2016).

Over time, sequence characterization has proven helpful in academic and industrial applications since such units constitute a natural structure for classification and local to regional correlations (e.g., Fragoso et al., 2021). Catuneanu and Zecchin (2013; p. 27) defined sequences as a "cycle of change in stratal stacking patterns, dividable into systems tracts and bounded by sequence stratigraphic surfaces". The current sequence-stratigraphic methodology has a scale-independent approach, in which sequences can be defined from the basin (sense Sloss et al.,1949; Sloss, 1963) to facies scale (e.g., Strasser et al., 1999; Magalhães et al., 2016; 2017; Figure 24), ordered in a hierarchical framework (Magalhães et al., 2020).

According to Fragoso et al. (2021), the characterization of sequences within a cyclic and hierarchical framework should obey the following criteria (Figure 25): transgressive-regressive (T-R) cycle anatomy; vertical recurrence of stacking patterns; vertical trends in the stacking patterns composing subsequent hierarchies of cyclicity; recognizable mappability. In this sense, a stratigraphic sequence framework is composed of cycles observed at different hierarchies. A higher ranking comprises an organized cluster of lower-ranking sequences (Catuneanu, 2019a; 2019b; Magalhães et al., 2020; Fragoso et al., 2021; Figure

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26). This cyclic approach of the stratigraphic analysis supports the objective results in predicting the vertical recurrence and the lateral correlation of genetic stratigraphic units.

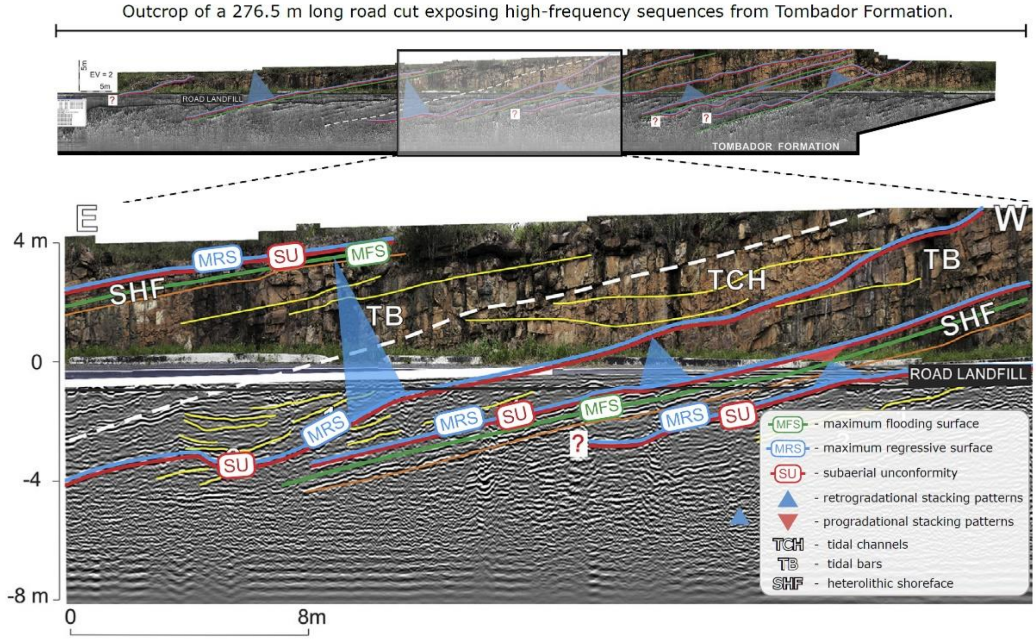

Figure 24. High-frequency sequences identified in an outcrop and in a GPR profile of the Tombador Formation (Mesoproterozoic), Chapada Diamantina Region, Brazil (modified from Magalhães et al., 2017). The sequences are composed of tidal channels and bars, bounded at the top by heterolithic intervals that configure cycles of retrogradational stacking patterns defined by the recurrence of the same type of stratigraphic surface in the geological record.

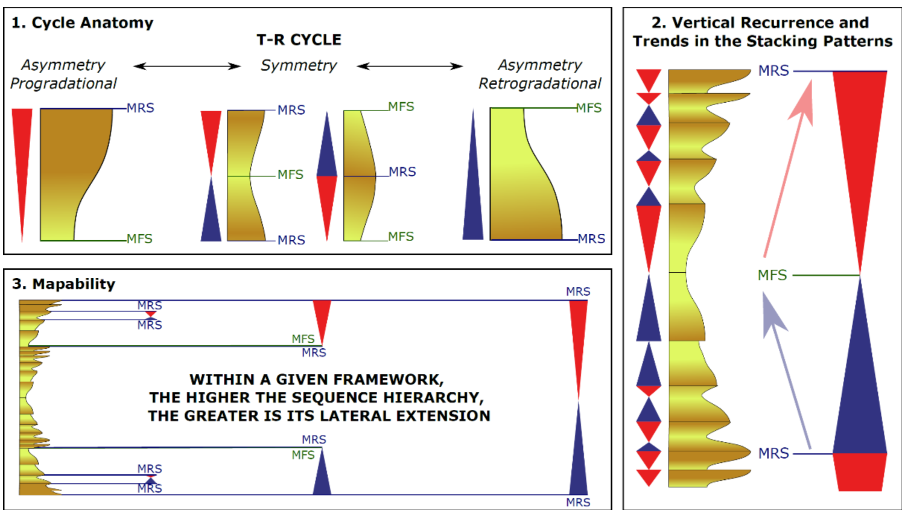

Figure 25. Characteristics and criteria for defining stratigraphic sequences within a cyclic and hierarchical framework (modified from Fragoso et al., 2021): 1. T-R cycle anatomy. 2. Vertical recurrence of individual cycles and trends in cyclic stacking pattern (modulation of the smallest by the highest hierarchy). 3. Mappability of the stacking patterns and stratigraphic surfaces within a given framework, which is more significant the higher is the hierarchy. Abbreviations: MFS – maximum flooding surface; MRS - maximum regressive surface.

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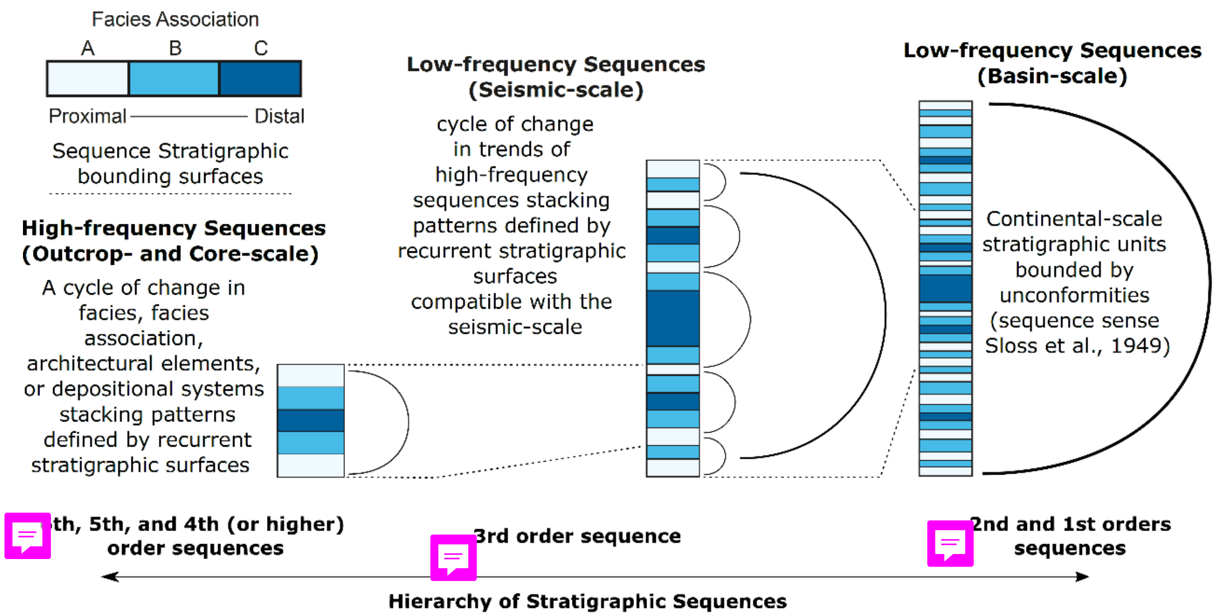

Figure 26. Hierarchical stratigraphic sequence framework (modified from Magalhães et al., 2020). High-frequency sequences (fourth or higher orders) are observed at outcrop- and core-scale. The vertical recurrence of high-frequency sequences composes the low-frequency sequences observed in seismic data (third-order). First- and second-order low-frequency sequences occur at basin-scale predominantly limited by unconformities, as proposed by Sloss et al. (1949).

3.4 Astrocycles

Gilbert (1895) was the first to consider that the sedimentary record may exhibit repetitions controlled by orbital cycles. He correctly suggested that the Upper Cretaceous marl-limestone alternation in the U.S state of Colorado should correspond to an allocyclic record of climatic oscillation controlled by the orbital precession cycle of about 20 kyr. Although rudimentary, Gilbert's conclusions allowed the measurement of geological time using the sedimentary record before the invention of radiometric dating (Strasser et al., 2006). After Gilbert, the studies of astronomically forced climatic cycles evolved considerably from Adhémar (1842), Croll (1875), and, especially, Milankovitch (1941). The application of this knowledge to sedimentary successions emerged gradually.

In the 1960s, some studies have started identifying cycles in different depositional contexts related to orbital forcing. For example, Van Houten (1964) presented the cyclic character of the lacustrine record of the Upper Triassic Lockatong Formation in the United States. This work stands out by determining a stratigraphic ordering in three hierarchies and proposing a temporal definition based on orbital cycles (Figure 27).

In 1976, one of the most influential articles in the study of Milankovitch's theory was published. In their work entitled "Earth Orbit Variations: The Ice Age Pacemaker", James Hays, John Imbrie, and Nick Shackleton established the effects of orbital parameters on the long-term climate record obtained from the analysis of marine sediments. Thus, Hays et al. (1976) "legitimized what was to become one of the most powerful tools in stratigraphy" (Maslin, 2016, p. 208).

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In the 1980s, the studies about the geological record of astronomical cycles integrated a subdiscipline of stratigraphy named "cyclostratigraphy" (Strasser et al., 2006). According to Hilgen et al. (2004), cyclostratigraphy identifies, characterizes, correlates, and interprets cyclical variations (periodic or quasi-periodic) in the stratigraphic record. In cyclostratigraphic studies, temporal calibrations can be done by either correlating sedimentary cycles – identified through variations in paleoenvironmental or paleoclimatic proxies sampled along a section or core (e.g., Li et al., 2019) – or by astronomical target curves of precession, obliquity and eccentricity, or by related insolation curves (Strasser et al., 2006). Weedon (2003) and Kodama and Hinnov (2015) present mathematical techniques for processing signals obtained by these proxies. Once the periodicity of a sedimentary cycle has been demonstrated, a very detailed analysis of sedimentological, paleoecological, or geochemical processes can be evaluated in a high-resolution time-stratigraphic framework (Strasser et al., 2006).

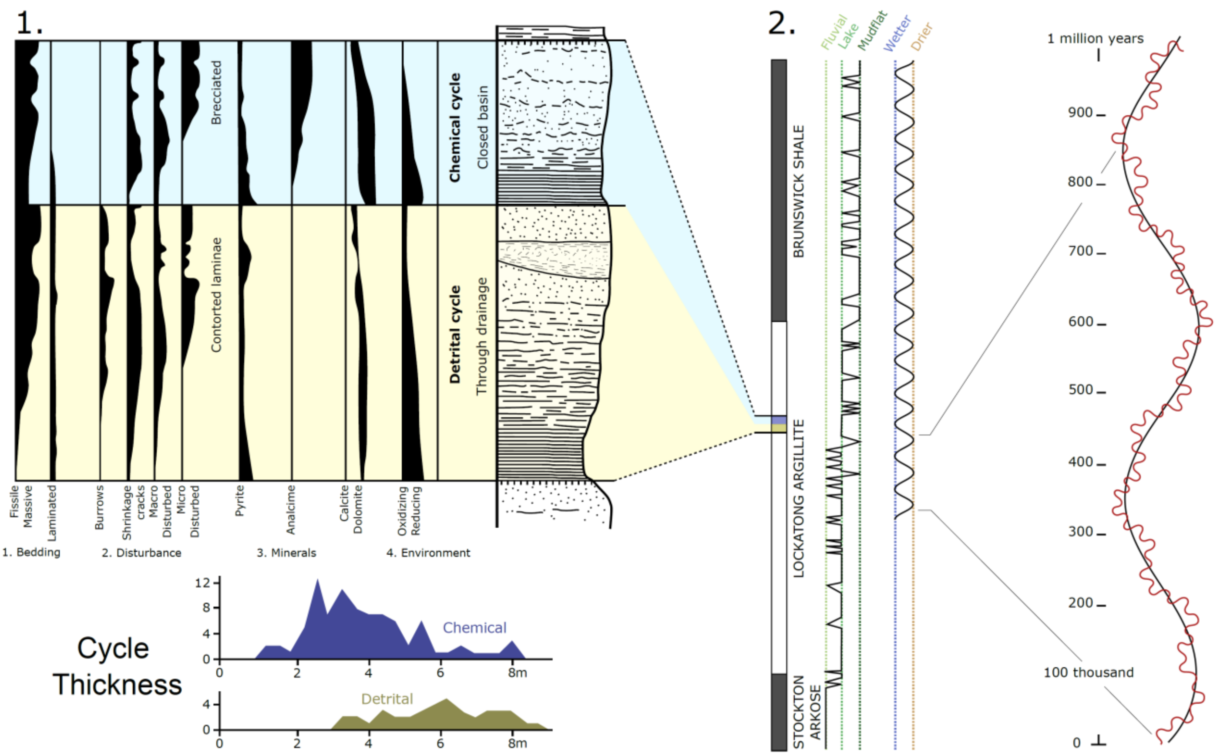

Figure 27. Cyclic lacustrine sedimentation of the Upper Triassic Lockatong Formation (modified from Van Houten,1964): 1. Model of detrital and chemical short cycles; 2. Generalized stratigraphic section of Lockatong Formation and adjacent units. The columns show the alternating geographic environments and the long climatic cycles of wetter and drier phases. An age model is presented based on two long climatic cycles, with intermediate and short cycles associated.

The term "sedimentary cycle" in cyclostratigraphy has a specific meaning, which differs from more generic applications (e.g., Weller, 1960). The sedimentary cycle as used in cyclostratigraphy corresponds to "one succession of lithofacies that repeats itself many times in the sedimentary record and that is, or is inferred to be, causally linked to an oscillating system and, as a consequence, is (nearly) periodic and has time significance" (Hilgen et al., 2004, p. 305; Figure 28). Thus, Strasser et al. (2006)

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proposed the term "astrocycle" to define specific cycles whose periodicity can be demonstrated by the cyclostratigraphic analysis.

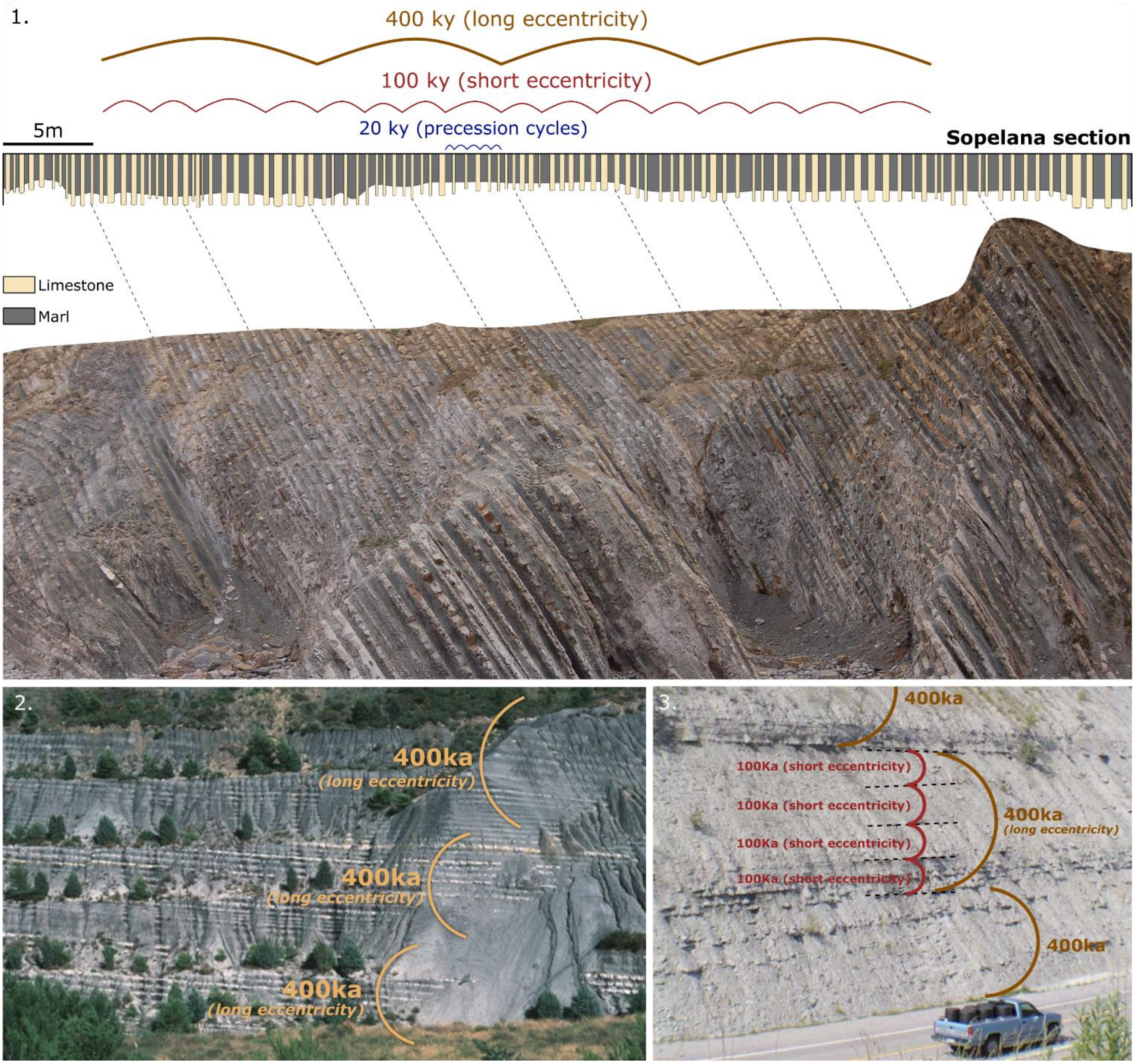

Figure 28. Outcrop examples of sedimentary cycles determined by cyclostratigraphic analysis: 1 – Long eccentricity, short eccentricity, and precession cycles in hemipelagic limestones and marls alternations of the Sopelana section (Maastrichtian), Spain (modified from Batenburg et al., 2014); 2 – Long eccentricity cycles in hemipelagic limestone and marl alternations of the La Marcouline section (Middle Aptian), France (modified from Kuhnt and Moullade, 2007); 3 – Long and short eccentricity cycles in shallow-marine deposits of the Kope Formation (Ordovician), United States (modified from Ellwood et al., 2013).

At this time, cyclostratigraphic analysis is part of integrated stratigraphy, which combines several stratigraphic subdisciplines (e.g., biostratigraphy, magnetostratigraphy, chemostratigraphy, geochronology) to solve problems related to geological time (Hilgen et al., 2015). This integration aids paleoenvironmental interpretation, focusing on multi-proxy analyses, and provides accurate geochronological information for astronomical tuning of stratigraphic records into target curves of orbital cycles and the related insolation curves. Thus, the integrated stratigraphy supports the construction of a high-resolution astronomical time scale that is currently decisive to determine a Global Stratotype Section and Point (GSSP – e.g., Lirer and Laccarino, 2011) and to refine the Geological Time Scale (Gradstein et al., 2021).

4 Discussion

Since the beginning of its existence, humans have dealt with cycles. From the simple day-night, hungry-satisfied, sleeping-awake to the passing of the seasons and the coming and going of migratory animals, the cycles are omnipresent and contribute to shaping the human way of thinking. This aspect certainly has had an epistemological influence on observing and interpreting the most diverse types of natural phenomena.

In Earth sciences, understanding the entire geological record starts with a primordial rock cycle, in which sedimentary processes are a fundamental part. The cyclic nature of the sedimentary processes is evidenced by multiple steps of erosion-transport-sedimentation experienced by any sedimentary particle from its source rock to its destination in a sedimentary basin. Biota also produce sediment, and their life cycles are controlled by cyclically changing environmental conditions. A harmonic produced by oscillations from different sources, frequencies, and amplitudes throughout this long sedimentation process modulates the final sedimentary product. Thus, the cyclical conception has an important implication for understanding the sedimentary record over geological time. In the big picture, the analysis of cyclicity is a crucial tool to correctly decode the sedimentary record (e.g., Barrell, 1917).

As can be seen throughout this brief review, the identification and interpretation of cycles correspond to a keystone in the history of stratigraphy. Despite the different approaches and nomenclatures, stratigraphic cycles have been described with very similar characteristics, such as stacking patterns, bounding surfaces, and hierarchical frameworks. This common thread of the different approaches paves the way for integrating efforts and the consequent methodological improvement. In this regard, integrated stratigraphy is undoubtedly the appropriate path by reinforcing the links between sequence stratigraphy and cyclostratigraphy (Fragoso, 2021). It is already known that many cycles used in cyclostratigraphy are well correlatable to sequences (Schwarzacher, 2000). Astronomical calibration of sequences is appropriate to reduce uncertainties regarding interpretations of changes in sea level, hydrodynamics, climate, physical, chemical, and biological processes (Schwarzacher, 2000; Hilgen et al., 2004; Strasser et al., 2006; Fragoso et al., 2021).

The recognition of multi-scale stratigraphic cycles, associated with temporal calibrations that better define the relationship – simple or complex – of cause (geological process) and effect (observable stratigraphic entity), will undoubtedly boost the current three-dimensional simulations of depositional systems. In this stratigraphic forward modeling, such parameters have already been used to simulate the genesis of low- to high-frequency sequences in 3D models applied to oil and natural gas exploration and production projects (e.g., Huang et al., 2015; Faria et al., 2017).

Another beneficial aspect of cyclicity in stratigraphy is related to the potential quantitative approach. Efforts in developing mathematical and statistical tools to characterize stratigraphic cycles have been around for many years. Statistical distribution fitting (e.g., Pantopoulos et al., 2013), Markov chains (e.g., Krumbein and Dacey, 1969; Carr, 1982; Purkins et al., 2012), Fischer plots (e.g., Fischer, 1964; Read and Goldhammer, 1988; Husinec et al., 2008), time-series analysis (e.g., Schwarzacher, 1975; Hinnov and Park, 1998; Weedon, 2003; Martinez, et al., 2016), and automatic stratigraphic correlations (e.g., Nio et al., 2005; Behdad, 2019; Shi et al., 2021) are examples of techniques used in stratigraphic research for quantifying cycles. With the so-called digital transformation currently in force in many areas of knowledge, such quantitative approaches tend to be expanded. Thus, the knowledge acquired about the main cyclic characteristics observed in the sedimentary record over the past few years should be the plumb-line towards a digital revolution within stratigraphy.

In order to deeply understand the cyclicity concepts in geological thinking, it is necessary to consider its ultimate root: thermodynamics (e.g., Richet et al., 2010). The first law of thermodynamics, also known as the Law of Conservation of Energy, states that energy cannot be created or destroyed but can change from one form to another. In this sense, everything in the Universe can be classified as a form of energy, regardless of its physical nature. Thus, it is possible to convert energy into any different form, be it a rock, a tree, or a human being. When we consider the Law of Conservation of Energy applied to deep time, it becomes possible to define several and constant cycles of energy transformation, such as the rock cycle. However, in thermodynamics, the reversibility of natural processes only occurs when they do not lead to an increase in entropy. In this way, the cyclicity of geological processes does not show absolute stability, and transformations must be considered at an appropriate time scale. That is, both the planet's internal geodynamics and the complex astronomical system can be visualized as spiral cycles that constantly change at different time intervals (e.g., Schwarzacher, 1993).

It is challenging to think that the Earth itself is a specific product, in time and space, of the cyclic process of formation and destruction of stars, which has been repeated since the beginning of the Universe. Different chemical elements are formed at each new cycle and subtly change the star nebulae composition resulting from the great supernova explosions. If it were not for the existence of one of these nebulae, with a particular chemical composition inherited from these past cycles, hovering in a specific corner of the Via Lactea 4.6 Ga ago, we would not have the Earth system as we know it today. Carl Sagan once said, "we are all made of stardust". Stardust on a journey of vast cyclic transformation.

Data availability

No data sets were used in this article

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Author contributions

DGCF conceived the presented idea, wrote the manuscript draft, prepared the figures, and made changes to the manuscript according to the reviewers suggestions. MK, AJCM, CMSS, GPRG and AS reviewed and improved the manuscript through corrections and suggestions.

Competing interests

The authors declare that they have no conflict of interest.

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