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Progress in the Study of Precambrian Systems Using Cyclic Stratigraphy

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ABSTRACT

The history of Earth's evolution shows that environmental changes have led to multiple major biological evolution events and altered the course of life evolution on Earth. Clarifying the timing and underlying mechanisms of these environmental upheavals is of great significance for us to respond to today's global changes. The Pre Cambrian period occupies the vast majority of geological history, exhibiting changes and evolution in atmospheric composition, paleoclimate, life, and other aspects at different time scales. In recent years, a large number of reliable Milankovitch cycle records have been identified in pre-Cambrian strata worldwide. With the help of various sedimentary cycle analyses, it is expected to establish a high-resolution chronological framework for the early evolution of the Earth, obtain data on planetary orbital interactions, and reconstruct the history of celestial dynamics. Through the main examples of pre-Cambrian cycle stratigraphy research, this paper analyzes the key issues and main challenges of pre-Cambrian cycle stratigraphy research, such as alternative indicators of primitive climate, reconstruction of celestial dynamics models, complex climate models, and paleogeographic uncertainties. It attempts to propose solutions to these problems.

KEYWORDS

Cyclic stratigraphy; Pre Cambrian period; Milankovitch cycles.

1. INTRODUCTION

During the pre Cambrian period, which occupied most of the geological history, the Earth experienced a series of significant geological events such as an increase in atmospheric oxygen content, drastic climate changes, early life evolution, and supercontinent reorganization. In recent years, there has been a rapid increase in research on the geology of the pre Cambrian period. However, the low resolution time frame fundamentally restricts scholars' in-depth exploration of many cutting-edge issues related to the coordinated evolution of multiple layers, which limits the research level of pre Cambrian geology[1]. The development of cyclic stratigraphy has played a great role in solving the problem of age accuracy. Previous researchers have identified reliable Milankovitch cycles and established high-precision astronomical chronology standards through testing and studying alternative paleoclimatic indicator data sequences in continuous sedimentary strata, effectively solving the problems of age accuracy and duration of geological historical events[2,3]. Currently, cyclic stratigraphy in the Mesozoic and Cenozoic is relatively complete. The study of Paleozoic cyclical stratigraphy is also making significant progress[4]. On the other hand, stable cyclic signals can be extracted from the Early Paleozoic Cambrian to Late Paleozoic Permian, from greenhouse climate to cold ice ages[5]. These achievements provide a solid foundation for the study of cyclical stratigraphy in the pre Cambrian period.

2. CYCLOSTRATIGRAPHY

2.1. Development of cyclic stratigraphy

In 1988, A.G. Fischer and I. Premoli Silva proposed cyclic stratigraphy at an academic conference held in Perugia, Italy. It is a new discipline formed by the combination of astronomy and stratigraphy, born from the exploration of marine strata. Nowadays, scholars have gradually introduced cyclical stratigraphy in the study of terrestrial strata. The overall development of cyclic stratigraphy has three stages:

2.1.1. Sprout stage

At the beginning of the 19th century, astronomers began to use the periodic changes in Earth's orbit to interpret meteorological changes. Lyell believes that changes in the geometric shape of the Earth's orbit can have an impact on climate, and these changes may also have important implications for geology[6]. Lyell's viewpoint has drawn attention to the potential geological significance of precession cycles. Herscher pointed out that the annual total daily sunlight on the Earth's surface does not change within a precession cycle, and thus proposed research on slope and eccentricity cycles[7]; Lyell discussed the role of astronomical changes in climate change in "Principles of Geology"[6]; Gilbert first applied the theory of sedimentary cycles combined with astronomical orbits to the Late Cretaceous interbedded sediments, accurately explaining their control by precession cycles and calculating the local sedimentation time of the Cretaceous system[8].

The fundamental understanding of many scholars in the embryonic stage has provided rich thinking support for subsequent researchers, and these exploratory studies have laid the foundation for the development direction and process of cyclical stratigraphy.

2.1.2. Rapid development stage

After initial exploration in the previous stage, cyclical stratigraphy finally achieved a qualitative leap in the rapid development of the 20th century. In the development stage, cyclical stratigraphy established a complete theoretical system and obtained technical confirmation.

Bradley studied the Eocene Green River Formation and calculated a 21ka precession cycle through its lacustrine layers. Milankovitch is dedicated to analyzing the relationship between orbital climate cycles and quantified sunshine intensity, and he has shown that the decrease in summer sunlight in the northern hemisphere leads to the formation of ice ages[9]. This discovery opened the era of studying high-frequency geological age. Due to his outstanding contribution, the theory of cyclic stratigraphy is also named after him, namely Milankovitch theory; Hays used spectral analysis of radiolarian relative abundance and oxygen isotopes, combined with summer sea surface temperature, to demonstrate that climate change during the Late Pleistocene was influenced by eccentricity, slope, and precession orbital period[10]. Hays' discovery is one of the key milestones in the development of cyclic stratigraphy.

Afterwards, the cyclical strata began a new stage, and more and more scholars paid great attention to it.

2.1.3. Actual application stage

At this stage, the study of cyclical stratigraphy has ushered in an unprecedented prosperity. Scholars from various fields such as paleoclimatology, geology, and paleoceanography have applied the Milankovitch theory as a new approach to conduct in-depth research and exploration in different fields. At the "Global Sedimentary Geology Project" conference held in Italy, Fischer pointed out that the tilt of the Earth's axis and the disturbance of the Earth's orbit cause periodic phenomena in cyclic strata, and astronomical cyclic periods are used to interpret repeated records in strata. Previously, cyclical stratigraphy had not been precisely defined; Thomas J. Gorgas used spectral analysis to calculate the natural gamma and density data of the Late Miocene in southwestern South Africa, obtaining their sedimentation rates. This technique not only became a new method for calculating sedimentation rates, but also demonstrated the possibility of sediment changes over time in the region; Hilgen improved the theory of cyclical stratigraphy, which is a branch of stratigraphy used to identify, interpret, and compare periodic and near periodic changes in stratigraphic records, and to improve the resolution and accuracy of stratigraphic time in geochronology; Based on the combination of relativistic effects and tidal friction factors, Laskar used a quantitative formula and analytical method to calculate the orbital parameters of the Earth, and applied numerical integration algorithm to obtain the astronomical orbital period and sunshine variation curve of the Earth over the past 250 Ma; Gradstein used astronomical orbital periods to divide and compare the strata of the Cenozoic, Early Cretaceous, Early Jurassic, and Late Triassic periods, determining the durations of the Quaternary, Neogene, and Paleogene periods, and compiled them in the 2004 International Geological Chronology; Hemmo A. Abels et al. used high-resolution color ratio data as a substitute indicator in their study of high-frequency cycles in the Miocene sedimentary strata of the Madrid Basin, demonstrating that long eccentricity periods may play a significant driving role in the filling of continental basins.

In the latest international geological chronology, the Triassic, Jurassic, and Cretaceous periods of the Mesozoic era have been calibrated using millions of years of long cyclic stratigraphic sequences [11]. At present, the research scope of cyclic stratigraphy has extended from the Quaternary to the Paleozoic, from marine strata to terrestrial basins. Its research methods are diverse and effective, and it is one of the main methods for studying oceanic sedimentation, stratigraphic analysis, and paleoclimate restoration.

2.2. Theoretical basis of cyclic stratigraphy

Cycle in sedimentology and stratigraphy refers to sedimentary records with reproducibility or periodicity, which can reflect the periodicity of sedimentary processes [12]. In general, cycles can be divided into sedimentary cycles caused by periodic changes in water depth under structural control, and cycles caused by periodic changes in climate under the control of Earth's orbital factors. The cycle in cyclical stratigraphy is the latter of the above, which is formed under the driving force of changes in Earth's orbital parameters, and is a phenomenon of repeated occurrence of sedimentary records and lithological changes related to periodic changes in sedimentary systems. It is precisely because the orbital changes of the Earth are periodic that the cyclical stratigraphy that records these periodic changes is endowed with temporal significance [2]. Therefore, the important research object of cyclical stratigraphy is the time series of changes. Researchers artificially divide the cyclicality reflected in geological records into different levels of cyclic sequences, and distinguish the orderliness of their stacking patterns, making it an important method for studying and identifying the spatial and relative temporal variations of sediments and sedimentary processes. At the same time, it also provides good historical evidence for the theory of orbital period driven sedimentary rhythms[13].

The Milankovitch cycle theory, as the theoretical basis for studying cycle stratigraphy, refers to the cycle stratigraphy recorded in the strata caused by periodic changes in Earth's orbital parameters. It explores the relationship between the Earth's climate system and the total amount of solar radiation on a global scale, and its corresponding orbital period is the Mie orbital period, also known as the Mie period[14].

The Milankovitch theory holds that when the Earth revolves around the Sun and rotates around its own axis, it is also influenced by the gravitational pull of other celestial bodies in the solar system. These influences cause the orbital parameters of the Earth's motion to exhibit periodic changes, thereby altering the amount of solar radiation received on the Earth's surface, resulting in periodic variations and ultimately leading to seasonal changes and differences in the climate system at high and low latitudes. This periodic variation can be compared at both geographical and global scales, ranging from tens of thousands to millions of years, and can be expressed using three major Earth orbit parameters: eccentricity, slope, and precession (Figure 1), which are also the three elements of Earth orbit that affect sunlight exposure. These three orbital elements all have quasi periodicity, and each element does not exist singly, usually containing multiple periodic values. This result is a manifestation of multiple interactions between planets in the solar system. According to different controlled factors, the orbital parameters of the Earth can be divided into two categories. One category is related to the dynamical system of the solar system, mainly including the elliptical orbital parameters of the Earth around the Sun, namely the orbital eccentricity; Another type is related to the interaction between the Earth and the Moon, mainly including the precession and slope of the Earth[15].

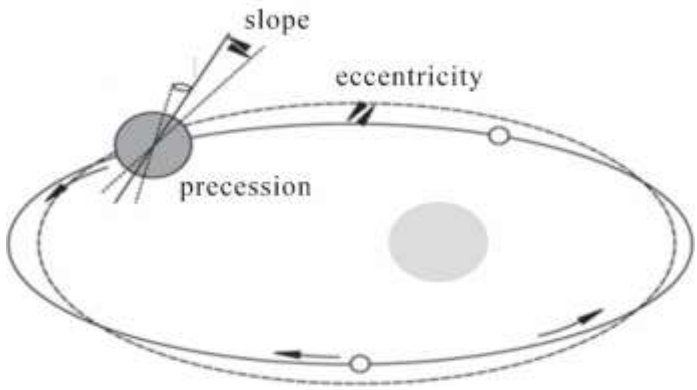

Figure 1. Schematic diagram of Earth's orbital parameters

2.2.1. Dynamics of the Solar System - Orbital Eccentricity Rotation

Orbital eccentricity is the ellipticity of the elliptical orbit of the Earth around the Sun. According to La2004's calculation model, the variation of eccentricity over the past 40 Ma ranges from 0.00021318 to 0.0669575, with periods mainly including 95000 years, 99000 years, 124000 years, 131000 years, and 405000 years. Among them, the amplitude of short eccentricity (e) around 100000 years is modulated by the amplitude of long eccentricity (E) around 405000 years. The 405000 year long eccentricity period is formed by the interaction between the perihelion of Venus and Jupiter orbits. The chaotic behavior of the solar system may affect Earth's 100000 year short eccentricity cycle, but the 405000 year long eccentricity has remained relatively stable for at least 250 million years in the past, and Jupiter's massive mass is the main reason for the relatively stable 405000 year cycle[16]

2.2.2. Earth Moon Interaction - Slope and precession cycles

The slope of the Earth's axis is the angle between the plane of the Earth's orbit around the Sun and the equatorial plane, with a range of 22.5° to 24.5°. Currently, it has a main period of 41 ka and sub periods of 39 ka, 54 ka, and 29 ka. The change in slope has a significant impact on high latitude regions. The larger the slope, the more sunshine received in high latitude summer, and the less sunshine received in winter, resulting in a larger temperature difference; On the contrary, the smaller the slope, the less sunlight is received in high latitude summer, and the more sunlight is received in winter, resulting in a smaller temperature difference. Precession, also known as precession, is the precession of the Earth's rotational axis around the vertical axis of the ecliptic plane. The main cycles of the current precession are 24ka, 22ka, and 19ka, and are clearly determined by the eccentricity and g4-g3 super eccentricity annual precession, which determine the timing of seasonal occurrence. If the summer solstice in the northern hemisphere reaches the aphelion and the winter solstice is located at the perihelion, then winter becomes shorter and the temperature rises, and the seasonal changes are not significant; On the contrary, if the winter solstice in the northern hemisphere reaches the aphelion and the summer solstice reaches the perihelion, the winter will become longer and the temperature will decrease, and the seasonal differences will increase[15].

Numerous geological evidences indicate that the Earth's rotation rate has decreased over the past 2 billion years, and the deceleration has undergone significant changes, even showing clear signs of reversal (Hinnov, 2018). Previous researchers have roughly estimated the precession and slope cycle periods of geological historical periods using various methods (Table 1). Some methods assume that the rate of lunar regression is constant (Laskar et al., 2004), some methods assume that tidal time differences are constant (Berger&Loutre, 1994), and some methods integrate the two and provide estimates of error intervals[17]

2.3. Research methods for pre Cambrian cycle stratigraphy

The most fundamental and direct method of studying cyclic stratigraphy in any geological period is the direct observation of lithology. For rhythmic strata with significant differences in sedimentary lithology, similar sedimentary styles and style combinations between different levels can be identified through observation of continuous outcrops or core lithology. If the evolution of lithology is proportional to the various astronomical periods at that time, there is evidence to suggest that this evolution was influenced by astronomical forces. However, in practical operation, it is often difficult to identify the differences in lithology between deep-sea and some lacustrine sedimentary rocks with the naked eye. Therefore, it is necessary to use quantitative or semi quantitative data obtained from alternative climate and environmental indicators to establish sequences based on depth[1]. The indicators we commonly use include K, U, and Th radioactive elements, magnetic parameters such as magnetic susceptibility and non hysteresis remanence, oxygen, carbon isotopes, and element content in rock formations tested by natural gamma. The selection of indicators is extremely important in the study of cyclic stratigraphy, considering factors such as: (1) whether the selected indicators are accurate and reliable; (2) Time and cost issues, such as stable isotopes of carbon and oxygen, can serve as good environmental alternative indicators, but the time and testing costs required for collecting and testing thousands of samples are high, making it difficult to complete. The magnetic susceptibility index can accurately and reliably record ancient environmental signals with low time and economic costs, making it an ideal alternative index for ancient environments[12]

Magnetic susceptibility (MS) refers to a dimensionless magnetic parameter of the degree to which a substance is magnetized in a magnetic field, with the international unit standard being (SI). Magnetic minerals generally include three types: paramagnetic minerals, ferromagnetic minerals, and diamagnetic minerals. Common paramagnetic minerals include mica, dolomite, and pyrite, which are positive values, while diamagnetic minerals include quartz and calcite, which are negative values; Ferromagnetic minerals include magnetite and hematite, and the magnetic susceptibility in rocks is the sum of the magnetic susceptibility of various magnetic minerals in the sample. These magnetic minerals typically come from terrestrial detrital inputs, or river or aeolian sources.

3. THE MAIN CHALLENGES FACED IN THE STUDY OF PRECAMBRIAN CYCLICAL STRATIGRAPHY

The Precambrian cyclical stratigraphy has enormous potential, but also faces unique challenges, such as the lack of evolutionary orbital astronomical theoretical models; The long age leads to incomplete geological records; Reliability and response mechanism of alternative indicators; The complexity of climate models and the uncertainty of paleogeography, among others.

The first is the lack of evolutionary orbital astronomical theoretical models. The long and short eccentricity periods are relatively stable during geological history, while the slope and precession period require the application of an axial precession constant when calculating theoretical values; The value of k is significantly influenced by the Earth Moon system and shows a gradually decreasing trend throughout geological history as the moon retreats. When matching the high confidence frequency components extracted from the depth curve corresponding to climate alternative indicators with each orbital period, unlike the modern clear 1:2:5:20, the slope and precession periods of the Pre Cambrian period are closer, partially overlapping and difficult to distinguish, and theoretically, the slope period and short eccentricity period of a certain era can also exhibit a 1:4 ratio, resulting in ambiguity[17]. To address this issue, a relatively accurate model of the evolution of the Earth Moon system has been established. Previous attempts have assumed that the lunar retreat velocity is a constant value[18] and the tidal delay is a constant value[16]. However, both schemes have been proven ineffective in practical applications. Using modern retreat speeds will overestimate the distance between the Earth and the Moon during geological periods, while using current tidal delays will underestimate this distance. The currently applicable method is to calculate the Earth's rotation speed based on the contemporaneous ancient tidal rhythm as a constraint, using at least two known endpoints (4.5Ga and modern Earth Moon distance) to establish a lunar retreat model for calculation[17]. The ancient tidal rhythm can be recorded in certain specific rhythmic layers, such as layered stones and BIF layers With the continuous achievement of new high-precision ages in recent years, research has been better constrained, and more and more reliable results of cyclical stratigraphy have been obtained. Through inversion, people are gradually establishing more realistic lunar retreat models.

The second issue is that the geological records available for research are relatively old, and the reliability of climate alternative indicators is also affected, facing the problem of how to properly explain their response mechanisms. Due to the influence of a long process of tectonic movement, the pre Cambrian strata are sometimes subjected to varying degrees of later metamorphic transformation. Compared to the Phanerozoic era, there are relatively few well preserved stratigraphic records of the Precambrian period that record primitive environmental information. At the same time, there is a relative lack of research on the sedimentary evolution of tectonic basins, which increases the difficulty of studying cyclical stratigraphy. It is essential to conduct basic petrographic research when solving such problems. For example, cathodoluminescence, electron microscopy backscattering, main and trace element ratios, and energy spectrum testing can be used to evaluate the possible diagenetic effects of pre Cambrian carbonate rocks. Selecting multiple independent parameters indicating the same climate influencing factor for correlation analysis can also demonstrate its endogeneity[12]. Meanwhile, due to the greater emphasis on identifying periodic components in cyclic stratigraphy compared to the accuracy of parameter absolute values, it is also one of the methods to demonstrate that the indicators used undergo overall synchronous changes[14].

The third is the complexity of climate models. Unlike the short-lived Phanerozoic polar ice sheet models, current research shows that environmental models from the pre Cambrian period exhibit significant differences in terms of extreme behavior, intense changes, and duration. The existence of both the extremely cold "snowball Earth" climate characterized by at least two global glacier occurrences and the so-called "dry billion year" period of polar ice free, persistent and stable greenhouse climate suggests that the drastic climate changes in the pre Cambrian period were influenced by changes in solar radiation caused by Earth's thermal evolution and astronomical drivers. To what extent do the driving forces inside and outside the Earth affect the climate? To solve this problem, it is still necessary to start with reliable geological evidence and analyze the cyclic structure based on basic cyclic stratigraphy research. By analyzing the response of various signal amplitude changes to major climate transition periods and extracting special signals such as half precession signals, the degree of influence of astronomical driving on climate can be determined and ancient climate models can be reconstructed.

The fourth is the uncertainty of ancient geography. The driving mechanisms of climate vary across different latitude zones, and the climate communication and oceanic thermohaline circulation between the northern and southern hemispheres are also influenced by the paleogeographic distribution of land and sea. Does the unique distribution of land and sea reflect a similar air sea coupling mechanism to modern times? Previously, the convergence and dispersal of the Nuna (Columbia) and Rodinia supercontinents during the Cambrian period provided a research basis for the reconstruction of global paleocontinent and paleogeographic location through methods such as paleomagnetism and plate tectonics reconstruction. The research results of paleomagnetism and chronology in the South and North China plates have brought some special opportunities for subsequent work. Paleomagnetic evidence shows that the South China Plate is currently the only region in the world that has undergone a process of moving from high latitudes or even polar regions to the equator during the Rodinia supercontinent. The North China Plate underwent a rapid process of moving from the equatorial region to the polar region and then back to the equatorial region from the Nuna supercontinent to the Rodinia supercontinent[12].

4. SUMMARY

With the basic completion of astronomical age correction in the Mesozoic and Cenozoic eras, and the gradual establishment of the Paleozoic astronomical age scale, the study of Precambrian cycle stratigraphy is an important research direction for the future. Current research indicates that there were astronomical cycles during the Pre Cambrian period, but quantitative studies of cyclic stratigraphy still require more case studies. The increase in high-precision absolute ages of the pre Cambrian period in the future, the improvement of the history of celestial dynamics evolution, and the optimization of statistical astronomical testing methods will rapidly promote the development of pre Cambrian cycle stratigraphy research[1].

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