

Recent Progress in Chinese Cyclostratigraphy and Its Earth System Science Implications

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ABSTRACT

Cyclostratigraphy has made significant progress in China in interpreting deep-time sedimentary records, astronomical chronology modeling, and energy exploration applications, providing critical support for Earth system science research. Through lithological assemblage and spectral analysis, Milankovitch cycle signals from multiple geological periods have been successfully identified, revealing the coupling relationship between climate change and sedimentary processes and providing high-resolution temporal frameworks for paleoclimate and paleoenvironmental reconstructions. In astronomical chronology modeling, high-precision astronomical time scales have been established using continuous sedimentary records such as the Cretaceous in the Songliao Basin, achieving temporal correlation between different sedimentary facies and promoting the accuracy of geological time frameworks. In energy exploration applications, cyclostratigraphy provides high-precision stratigraphic division and correlation methods for unconventional oil and gas resources such as shale oil, clarifying the spatiotemporal evolution of shale oil reservoir quality and significantly improving exploration efficiency. However, technological bottlenecks remain, including insufficient data quality and resolution, lack of deep interdisciplinary integration, and unclear response mechanisms in complex sedimentary environments. Future development directions include technological innovation and interdisciplinary integration, big data and artificial intelligence applications, and international cooperation and exchange, to further promote the development and application of cyclostratigraphy and provide stronger support for Earth system science.

KEYWORDS

Cyclostratigraphy; Milankovitch cycles; Astronomical tuning; Earth system science; Unconventional oil and gas

1. INTRODUCTION

1.1. Theoretical origin of cyclostratigraphy

The theoretical foundation of cyclostratigraphy originated in the early 20th century when Serbian scientist Milutin Milankovitch proposed the link between variations in Earth's orbital parameters and climate change[1]. Milankovitch mathematically demonstrated that periodic changes in Earth's orbital eccentricity, precession, and obliquity alter the amount of solar radiation received by the Earth, thereby influencing global climate. This theory was not widely recognized in the geological community until the 1970s, when scientists confirmed the existence of Milankovitch cycles through oxygen isotope records in deep-sea sediments, ushering in a new era of modern sedimentary cycle analysis[1].

From Milankovitch theory to modern sedimentary cycle analysis, cyclostratigraphy has undergone a disciplinary evolution from theoretical hypothesis to empirical research. With the interdisciplinary

integration of geology, geophysics, geochemistry, and other fields, the research methods and technical approaches of cyclostratigraphy have been continuously enriched and refined. The construction of high-resolution time scales has become one of the international research hotspots in this field[2]. Through the identification and analysis of cyclic signals in sedimentary records, scientists can establish high-precision temporal frameworks, achieve temporal correlation between different sedimentary facies, and provide important tools for precise dating of geological events. Additionally, quantitative paleoclimate inversion is also an important research direction of cyclostratigraphy. Through quantitative analysis of cyclic signals in sedimentary records, scientists can reconstruct the variation history of paleoclimate parameters, reveal the evolutionary patterns of the Earth's climate system, and provide historical background and theoretical basis for understanding modern climate change[3, 4].

1.2. Formation of Chinese research characteristics

Chinese cyclostratigraphy research has gradually formed a distinctive system by inheriting international advanced theories and technologies. China possesses abundant continental basin sedimentary records with complex and diverse depositional environments and rich cycle signals[5], providing unique conditions for cyclostratigraphy research. Compared with marine depositional systems, continental systems are more susceptible to combined influences of tectonic activity, climate change, sediment supply, and other factors, making the identification and interpretation of cycle signals more challenging. However, this very complexity makes continental basins ideal venues for studying multi-process coupling in Earth systems. Through research on continental basin sedimentary records, Chinese scholars have made significant progress in deep-time sedimentary record interpretation, astronomical chronology modeling, and energy exploration applications, contributing substantially to the development of Earth system science[6, 7].

National energy strategic demands constitute an important driving force for the development of cyclostratigraphy in China. As the country's demand for energy resources continues to increase, the development of unconventional oil and gas resources has become a crucial component of energy strategy. Cyclostratigraphy holds significant application value in the exploration of shale oil, shale gas, and other unconventional resources. Through the study of sedimentary cycles, scientists can perform high-precision stratigraphic division, predict the distribution patterns of oil and gas reservoirs, improve exploration efficiency, and reduce exploration risks. Therefore, national energy strategic demands not only provide broad application prospects for cyclostratigraphy research but also promote continuous innovation in the discipline's theories and technologies.

Within the Deep-time Digital Earth (DDE) big science program, the disciplinary positioning of cyclostratigraphy is particularly important. The DDE program aims to construct digital models of Earth systems through multidisciplinary integration, achieving comprehensive reconstruction and deep understanding of Earth's evolutionary history. As a key discipline connecting geological time scales and Earth system processes, cyclostratigraphy can provide high-precision temporal frameworks and rich geological information for the DDE program[8]. Through the study of sedimentary cycles, scientists can reconstruct the history of paleoclimate and paleoenvironmental changes, reveal interaction mechanisms among different spheres of the Earth system, and provide important theoretical support and technical guarantees for the implementation of the DDE program.

2. RESEARCH PROGRESS OF CYCLOSTRATIGRAPHY IN CHINA

In recent years, Chinese cyclostratigraphy has achieved remarkable progress in methodology, typical basin studies, and technical equipment localization, promoting disciplinary development and providing important theoretical and technical support for geology, Earth system science, and energy exploration.

2.1. Methodological innovations

2.1.1. Localization of astronomical tuning technology: Cretaceous lacustrine cycle identification system in the Songliao Basin

Astronomical tuning is a core method of modern cyclostratigraphy. By linking cycle signals in sedimentary records to astronomical orbital parameter variations, high-precision time scales can be constructed[2, 9]. The research team led by Wang Chengshan successfully localized astronomical tuning technology in the study of Cretaceous lacustrine deposits in the Songliao Basin, developing a complete lacustrine cycle identification system. This system integrates high-resolution well logging data, core analysis, and geochemical indicators, identifying Milankovitch cycle signals in the Songliao Basin Cretaceous succession and establishing a high-precision astronomical time scale.

The Songliao Basin is one of China's important continental sedimentary basins, with complete and continuous Cretaceous lacustrine records providing ideal material for astronomical tuning. Through high-density well logging and core analysis of multiple drill holes in the Songliao Basin, the team identified sedimentary cycles corresponding to astronomical orbital parameters including eccentricity, precession, and obliquity[10-14]. The study revealed that Songliao Basin lacustrine deposits respond significantly to astronomical cycles, particularly in eccentricity and precession periods, with cycle identification precision reaching the meter scale. This achievement not only provides a high-precision temporal framework for the basin's geochronology but also serves as an important reference for astronomical tuning research in other continental basins[15].

2.1.2. Artificial intelligence drive: CNN-based automatic cycle identification algorithm

With the rapid development of artificial intelligence technology, its application in geology has attracted increasing attention. In 2021, a research team from China University of Geosciences developed a convolutional neural network (CNN)-based automatic cycle identification algorithm, providing new technical means for cyclostratigraphy research.

This algorithm uses deep learning technology to automatically identify and classify cycle signals in sedimentary records. The research team trained CNN models using large amounts of sedimentary data, enabling recognition of sedimentary cycles corresponding to astronomical orbital parameters such as eccentricity, precession, and obliquity. Compared with traditional manual identification methods, the CNN-based algorithm significantly improves identification accuracy and efficiency. This technology not only provides new tools for high-resolution cyclostratigraphy research but also offers new approaches for geological big data processing and analysis.

2.2. Typical basin case studies

2.2.1. Tarim Basin: Cambrian high-frequency cycles and source rock development coupling mechanism

The Tarim Basin is one of China's important petroliferous basins, with abundant Cambrian sedimentary records of significant geological importance. In recent years, Chinese geologists have discovered a coupling mechanism between high-frequency cycles and source rock development in the Tarim Basin Cambrian.

Through high-resolution well logging and core analysis of the Tarim Basin Cambrian, the research team identified high-frequency sedimentary cycles and established corresponding astronomical time scales. The study found that Cambrian source rock development is closely related to eccentricity and precession cycles of sedimentary cycles. Under the control of these cycles, rapid changes in depositional environments provided favorable conditions for source rock formation. This research not only provides important geological evidence for oil and gas exploration in the Tarim Basin but also offers new perspectives for understanding the relationship between Cambrian depositional environments and source rock development[16-20].

2.2.2. Ordos Basin: Quantitative analysis of Milankovitch cycles in the Triassic Yanchang Formation

The Ordos Basin is one of China's important continental petroliferous basins, with complete Triassic Yanchang Formation sedimentary records of significant geological importance. In recent years, Chinese geologists have quantitatively analyzed Milankovitch cycles in the Ordos Basin Triassic Yanchang Formation through high-resolution well logging and core analysis.

Through high-density well logging and core analysis of multiple drill holes in the Ordos Basin, the research team identified sedimentary cycles corresponding to astronomical orbital parameters including eccentricity, precession, and obliquity[21], establishing corresponding astronomical time scales. The study revealed that Yanchang Formation sedimentary cycles respond significantly to Milankovitch cycles, particularly in eccentricity and precession periods, with cycle identification precision reaching the meter scale. This research not only provides a high-precision temporal framework for the Ordos Basin's geochronology but also serves as an important reference for astronomical tuning research in other continental basins[22-24].

2.2.3. South China Sea: Miocene astronomical time scale from IODP expeditions

The South China Sea is an important marginal sea of China, with sedimentary records significant for studying East Asian monsoon evolution and global climate change[25]. In recent years, the marine team from Tongji University successfully established a Miocene astronomical time scale through IODP expeditions in the South China Sea.

Through high-resolution well logging and core analysis of IODP expedition drill holes, the research team identified sedimentary cycles corresponding to astronomical orbital parameters including eccentricity, precession, and obliquity, establishing corresponding astronomical time scales. The study found that South China Sea Miocene sedimentary records respond significantly to Milankovitch cycles, particularly in eccentricity and precession periods, with cycle identification precision reaching the centimeter scale. This research not only provides a high-precision temporal framework for the South China Sea's geochronology but also offers new perspectives for understanding the relationship between South China Sea depositional environments and climate change[26-32].

2.3. Technical equipment localization

2.3.1. Domestic high-density gamma-ray spectrometry logging tool

High-density gamma-ray spectrometry logging tools are indispensable technical equipment in modern cyclostratigraphy research, providing high-resolution sedimentary records[33] for cycle identification and analysis. In recent years, the Research Institute of Petroleum Exploration and Development (RIPED), CNPC, successfully achieved localization of high-density gamma-ray spectrometry logging tools.

The domestic high-density gamma-ray spectrometry logging tool has reached international advanced levels in performance and precision, meeting the research needs of Chinese geologists in both continental and marine sedimentary basins. The successful application of this instrument not only reduces research costs but also improves data acquisition efficiency and quality. This achievement marks significant improvement in China's independent innovation capability in geological technical equipment, providing important technical guarantees for cyclostratigraphy research.

2.3.2. Micro-CT technology application in micron-scale sedimentary laminae analysis

Micro-CT technology enables high-resolution analysis of micron-scale sedimentary laminae, with applications in cyclostratigraphy research attracting increasing attention. Through high-resolution scanning and analysis of micron-scale sedimentary laminae, research teams can identify subtle changes in sedimentary cycles, providing important data support for depositional environment reconstruction and climate change inversion[34]. The application of Micro-CT technology not only

improves sedimentary cycle identification precision but also provides new technical means for studying cycle signals in complex depositional systems. This achievement marks significant improvement in the application level of China's geological technical equipment, providing important technical support for cyclostratigraphy research.

3. SCIENTIFIC AND SOCIAL VALUE OF CYCLOSTRATIGRAPHY RESEARCH

Cyclostratigraphy, as an important branch of geology, studies the rhythmic variation patterns in strata. It not only holds significant theoretical importance for the development of geological science but also demonstrates tremendous application value in energy exploration, paleoclimate and environmental reconstruction, and other fields, exerting profound influence on social progress and economic development.

3.1. Guidance for energy exploration engineering

In the context of increasingly tight energy resources, efficient and precise energy exploration technology is key to ensuring energy supply. Cyclostratigraphy has played an important guiding role in energy exploration, particularly in shale oil sweet spot prediction and reservoir heterogeneity analysis.

3.1.1. Shale oil sweet spot prediction: Cycle structure and organic matter enrichment in the Sichuan Basin

The Sichuan Basin is an important shale gas and shale oil resource enrichment area in China, where the Wufeng Formation-Longmaxi Formation strata are key targets for shale oil and gas exploration. Through in-depth study of cycle structures in this area, the internal connection with organic matter enrichment has been revealed, providing a strong basis for shale oil sweet spot prediction.

Research shows that the cycle structure of the Wufeng Formation-Longmaxi Formation in the Sichuan Basin exhibits obvious periodic changes closely related to depositional environments, paleoclimate conditions, and paleogeographic patterns at that time. In specific cycle stages, parameters such as sediment grain size, mineral composition, and organic matter content show regular variations. Through detailed division and analysis of these cycle structures, depositional environments favorable for organic matter preservation and enrichment can be identified, thereby determining the distribution areas of shale oil sweet spots. For example, in certain semi-deep to deep marine depositional environments, due to anoxic water bodies and low sedimentation rates, organic matter was preserved and enriched in large quantities, forming high-quality shale oil source rocks. Through cycle structure research, these favorable depositional environments can be accurately identified, providing precise targets for shale oil exploration and development, greatly improving exploration success rates, reducing exploration costs, and holding significant importance for ensuring China's energy security.

3.1.2. Reservoir heterogeneity analysis: High-resolution cycle division in the Daqing Oilfield

Reservoir heterogeneity is a key factor affecting oilfield development efficiency. Through high-resolution cyclostratigraphic division, the spatial heterogeneity of reservoirs can be accurately characterized. Through the study of cycle structures, water injection schemes can be optimized, production well patterns adjusted, oilfield recovery rates improved, and oilfield development lifespans extended, holding important value for ensuring the stable development of China's petroleum industry.

3.2. Paleoclimate and environmental reconstruction

Earth's climate system has undergone a long and complex evolution process. Reconstructing paleoclimate environments is of great significance for understanding the evolution of Earth's climate system and predicting future climate change trends. Cyclostratigraphy can provide high-precision temporal frameworks and rich environmental information for paleoclimate environmental reconstruction through analysis of cycle structures in strata.

3.2.1. Astronomical evidence for Cenozoic uplift of the Tibetan Plateau

The Cenozoic uplift process of the Tibetan Plateau is one of the most important geological events on Earth, profoundly influencing regional and global climate patterns. Through cyclostratigraphy research, an astronomical evidence chain for the Tibetan Plateau's Cenozoic uplift has been constructed, providing important basis for understanding the uplift process and its environmental effects [35]. For example, specific cycle stages may reflect rapid uplift of the Tibetan Plateau during certain periods, leading to more arid regional climates and thereby affecting surrounding ecological environments and biological evolution. Through the study of these cycle structures, the interaction between Tibetan Plateau uplift and climate change can be better understood, providing important regional cases for global climate change research.

3.2.2. High-precision temporal constraints on the end-Permian mass extinction

The end-Permian mass extinction is one of the most severe biological extinction events in Earth history. Through high-precision cyclostratigraphic research on Global Boundary Stratotype Section and Point (GSSP) sections, high-precision temporal constraints on the end-Permian mass extinction event have been provided, helping to understand the spatiotemporal characteristics of this event, providing important evidence for revealing major events in Earth life evolution, and offering historical lessons for modern biodiversity protection.

3.3. Contributions to earth system science theory

Earth system science emphasizes interactions and coupling relationships among Earth's various spheres. As an important component of Earth system science, cyclostratigraphy provides new perspectives and methods for the development of Earth system science theory through the study of strata cycle structures.

3.3.1. Reconsideration of Mesozoic greenhouse climate fluctuation mechanisms

The Mesozoic Era was a typical greenhouse climate period in Earth history. Through cyclostratigraphy research, the complexity of Mesozoic greenhouse climate fluctuations can be better understood, providing historical lessons for modern greenhouse climate research and offering new ideas and methods for the development of Earth system science theory.

3.3.2. Nonlinear modeling of astronomical orbital parameters on sedimentary processes

Astronomical orbital parameter changes have important influences on Earth's surface sedimentary processes; however, this influence is not a simple linear relationship but is closely related to factors such as tectonic activity, sediment supply, and sea level changes. Through the study of cycle structures, nonlinear relationship models between astronomical orbital parameters and sedimentary processes can be established, providing important theoretical support for deeply understanding the complexity of Earth's surface systems and offering new research directions for the development of Earth system science [36].

4. CONCLUSIONS AND PERSPECTIVES

4.1. Summary

Chinese cyclostratigraphy has made significant achievements in methodology, typical basin studies, and technical equipment localization. In terms of methodology, the localization of astronomical tuning technology and the development of artificial intelligence algorithms have greatly improved cycle identification accuracy and efficiency. In typical basin research, high-precision astronomical time scales have been established in the Songliao, Tarim, and Ordos basins and the South China Sea, revealing the coupling relationships between sedimentary cycles and source rock development, reservoir quality, and climate change. In technical equipment, the domestic high-density gamma-ray spectrometry logging tool and Micro-CT technology have reached international advanced levels, providing important technical guarantees for cyclostratigraphy research.

Cyclostratigraphy plays an important role in revealing the importance of deep-time geological records, polycyclic crustal evolution, and deep fault zone controls. The influence of surface systems on deep Earth spheres is most easily reflected in current deep structures, compositions, and geological process changes, which can be detected through geophysical means and traced through geochemical methods [37, 38]. Interactions among Earth spheres reveal that various spheres influence each other through topography, material, and energy exchange, playing key roles in the formation and evolution of Earth's critical zone, surface environment shaping, and ecosystem functions. Research on multi-sphere compound extreme events shows that under climate change backgrounds, the diversity and complexity of compound extreme events increase, posing serious threats to human society and natural ecosystems.

4.2. Future perspectives

Although Chinese cyclostratigraphy has achieved remarkable results, many complex interaction mechanisms remain to be fully elucidated, such as nonlinear feedback mechanisms in multi-sphere coupling processes. Current Earth system models have certain limitations in simulating multi-sphere interactions, with insufficient capabilities for simulating small-scale processes and sudden events. The synergy of interdisciplinary research needs further strengthening to promote deep integration among different disciplines [39].

Future research should further improve the understanding of interaction mechanisms among various spheres of the Earth system, provide stronger scientific support for addressing global challenges such as global climate change, ecological environment destruction, and natural disasters, and achieve sustainable development of Earth systems. This requires continuous technological innovation, strengthened interdisciplinary integration, application of big data and artificial intelligence, and expanded international cooperation and exchange, thereby promoting the in-depth development of cyclostratigraphy and providing more powerful support for Earth system science[40-44].

ACKNOWLEDGEMENTS

The author gratefully acknowledges the support from the Deep-time Digital Earth (DDE) Big Science Program and national strategic research projects in energy and Earth system sciences. Sincere thanks are extended to all researchers whose work has contributed to the progress of cyclostratigraphy in China.

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