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The Application and Influence of Stratigraphy in Paleoenvironmental Evolution Research

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Abstract: As an important branch of geology, stratigraphy and its recent advances play a key role in research on paleoenvironmental evolution. Through high-resolution sedimentary stratigraphic analysis, scientists can reveal changes in climate, geomorphology, and biodiversity throughout Earth's history. Recent stratigraphic research no longer relies solely on traditional sediment analysis, but also incorporates advanced techniques such as geophysical logging and environmental magnetism, thereby improving the accuracy and depth of data acquisition. These advances provide an important basis for paleoclimate reconstruction. For example, data such as trace-element contents and isotopic compositions in sediments can be used to reconstruct patterns of paleoclimate change with relatively high precision. At the same time, stratigraphic research also promotes the understanding of paleogeomorphic evolution and reveals geological phenomena such as river migration and landscape change. In addition, fossil records preserved in strata provide valuable materials for studies of paleobiodiversity and promote the development of biogeography, paleoecology, and related fields. Recent advances in stratigraphy not only enrich our understanding of paleoenvironmental evolution, but also provide a scientific basis for addressing modern climate change, resource exploration, and natural-disaster prevention. Therefore, they have far-reaching applications and impacts.

Keywords: Stratigraphy, paleoenvironmental evolution, stratigraphic analysis.

1. Overview of Recent Advances in Stratigraphy

In recent years, significant breakthroughs and innovations have been achieved in stratigraphic theory, technology, and methodology. These advances have greatly promoted the development of stratigraphy toward higher precision, higher resolution, and greater diversification. The following section summarizes these important advances [3].

1.1. Theoretical Breakthroughs

The theory of high-resolution sequence stratigraphy emphasizes the establishment of a high-precision chronostratigraphic correlation framework by using multiscale base-level cycles as reference surfaces. This theory not only improves the precision of stratigraphic subdivision, but also provides more reliable geological models for reservoir prediction [5, 8].

The application of this theory has significantly improved the resolution of stratigraphic subdivision, enabling stratigraphic research to reveal geological historical processes in greater detail and to provide more precise geological evidence for resource exploration and geological-disaster prevention.

By integrating research results from geochemistry, paleontology, isotope geology, and other disciplines, stratigraphers have gained a deeper understanding of stratigraphic evolution and paleoenvironmental reconstruction. For example, studies of Chang'e-5 lunar samples have renewed the understanding of lunar evolution and provided a new perspective for stratigraphic research beyond Earth.

These studies have not only enriched the theoretical system of stratigraphy, but have also promoted interdisciplinary integration between stratigraphy and other fields, forming a more diversified research pattern [13].

1.2. Technological Innovation

The use of advanced measuring instruments and data-processing methods has enabled high-precision measurements of geophysical fields. This has not only improved exploration accuracy, but also reduced exploration costs, providing richer data support for stratigraphic research.

The integration of geophysics with geology, geochemistry, remote sensing, and other disciplines has formed comprehensive exploration methods. Such interdisciplinary research methods not only improve exploration accuracy, but also promote the diversified development of stratigraphic research.

With the development of artificial intelligence and big-data technologies, geophysical exploration techniques have begun to move toward intelligent application. Automated data processing and interpretation improve exploration efficiency and accuracy, providing more convenient and efficient tools for stratigraphic research.

1.3. Methodological Innovation

Stratigraphic research increasingly emphasizes the integrated use of multiple methods and technical approaches. Through the comprehensive application of geological investigation, geophysical exploration, geochemical analysis, remote-sensing techniques, and other methods, an integrated research system has been formed. This comprehensive approach not only improves the scientific reliability and accuracy of research, but also promotes the diversified development of stratigraphic studies.

Using big-data and artificial-intelligence technologies to deeply mine and analyze stratigraphic data can reveal new stratigraphic patterns and characteristics. This research approach not only improves the precision and efficiency of stratigraphic research, but also provides new ideas and methods for the field.

1.4. Factors Promoting the Development of Stratigraphy toward Higher Precision, Higher Resolution, and Greater Diversification

The application of advanced measuring instruments and data-processing methods has improved the precision and efficiency of stratigraphic research; the development of intelligent technologies has made data processing and interpretation more convenient and efficient; and breakthroughs in drilling technology have enabled stratigraphic research to extend to deeper levels.

The interdisciplinary integration of stratigraphy with other disciplines has promoted the diversified development of stratigraphic research. By drawing on theories and methods from other disciplines, stratigraphic research can form a more integrated and comprehensive research system.

International cooperation and exchange provide broader platforms and more opportunities for stratigraphic research. By participating in international geological science and technology organizations and forums, stratigraphers can learn about international frontier trends and advanced technological achievements, thereby promoting the internationalization of stratigraphic research.

In summary, recent theoretical, technological, and methodological breakthroughs and innovations in stratigraphy have greatly promoted its development toward higher precision, higher resolution, and greater diversification. These advances not only enrich the knowledge system and research methods of stratigraphy, but also provide strong support for geological exploration, resource development, and environmental protection.

2. Applications of Recent Stratigraphic Advances in Paleoenvironmental Research

2.1. High-Precision Chronological Methods Providing an Absolute Time Framework for Paleoenvironmental Evolution

2.1.1. U-Pb Isotope Dating

U-Pb isotope dating is based on the radioactive decay between uranium (U) and lead (Pb) isotopes. Uranium isotopes, such as ^{238}U and ^{235}U, decay into lead isotopes, such as ^{206}Pb, ^{207}Pb, and ^{208}Pb, and the ratios of these decay products can be used to calculate the ages of rocks or minerals.

This method is widely applied to age determination of igneous, metamorphic, and sedimentary rocks, especially in geochronology, economic geology, structural geology, paleontology, and related fields. Through U-Pb dating, scientists can determine the exact timing of geological events such as volcanic eruptions, magma intrusion, and sediment deposition, thereby providing key time nodes for research on paleoenvironmental evolution.

The age data provided by U-Pb isotope dating constitute a cornerstone of the geological time framework, allowing scientists to accurately link paleoenvironmental evolution with specific geological time intervals and thereby reveal the evolutionary patterns of Earth's history.

2.1.2. Lu-Hf Isotope System

The Lu-Hf isotope system is used for dating based on the decay of lutetium (Lu) into hafnium (Hf). Similar to the U-Pb system, variations in Lu-Hf isotope ratios can be used to calculate the ages of rocks or minerals.

The Lu-Hf isotope system also holds an important position in geochronology and is particularly suitable for dating certain types of rocks, such as eclogite and peridotite. In addition, the Lu-Hf isotope system provides important information about crustal material recycling and mantle evolution.

Through Lu-Hf isotope dating, scientists can further understand the evolution of the crust and mantle in geological history, processes that are closely related to paleoenvironmental evolution. For example, crustal uplift and subsidence, volcanic activity, and magma intrusion can all have profound impacts on paleoenvironments.

2.2. Applications of High-Resolution Sequence Stratigraphy, Biostratigraphy, and Chemostratigraphy in Revealing High-Frequency Paleoenvironmental Changes

High-resolution sequence stratigraphy uses multiscale base-level cycles as reference surfaces to establish a high-precision chronostratigraphic correlation framework. Through detailed lithological subdivision and correlation, it reveals short-term stratigraphic cycles and subtle changes in depositional environments. This technique can identify smaller depositional units and finer sedimentary structures in strata, thereby revealing high-frequency paleoenvironmental changes. For example, in oil and gas exploration, high-resolution sequence stratigraphy can help predict reservoir distribution and properties; in paleoenvironmental research, it can be used to reconstruct the history of changes in environmental parameters such as paleoclimate and paleoflow direction [5, 8].

Biostratigraphy uses fossil records to infer geological history and paleoenvironmental evolution. Different types of fossils are often associated with specific geological ages and depositional environments. By analyzing fossil assemblages, distributions, and ecological characteristics in strata, scientists can reveal the succession of paleocommunities and their relationships with paleoenvironmental changes. For example, the appearance or disappearance of certain fossils may indicate environmental events such as climatic warming or cooling and sea-level rise or fall [2].

Chemostratigraphy infers paleoenvironmental evolution by measuring the chemical compositions of rocks, minerals, and sediments in strata and their variations. This technique can obtain multiple paleoenvironmental indicators, including paleoclimate, paleoflow direction, and paleo-redox conditions. For example, by measuring variations in stable isotopes, such as oxygen and carbon isotopes, it is possible to infer changes in paleotemperature and precipitation; by measuring the contents and distribution patterns of trace elements and rare-earth elements, it is possible to reveal paleoflow directions and sediment sources [1, 4].

2.3. Applications of Digital Stratigraphy and Three-Dimensional Stratigraphic Modeling in Three-Dimensional Visualization of Paleoenvironmental Conditions

Digital stratigraphy uses digital methods to process, analyze, and store stratigraphic data. By constructing digital stratigraphic models, rapid acquisition and sharing of stratigraphic data can be achieved. Digital stratigraphic techniques provide strong support for three-dimensional visualization of paleoenvironmental conditions. Through the construction of three-dimensional stratigraphic models, scientists can intuitively display the spatial distribution and morphological characteristics of strata, thereby revealing the spatial structure and evolutionary processes of paleoenvironments.

Three-dimensional stratigraphic modeling is based on geological data and uses computer graphics and visualization techniques to construct three-dimensional stratigraphic models. Such models can completely and accurately represent the boundary conditions of complex geological phenomena and the various geological structures contained within geological bodies.

3. Influence of Stratigraphic Advances on Paleoenvironmental Research

3.1. Recent Stratigraphic Advances Promoting Subdivision and Interdisciplinary Integration in Paleoenvironmental Research

The development of high-precision chronological methods, such as U-Pb isotope dating and the Lu-Hf isotope system, enables paleoenvironmental research to reach shorter time scales and finer spatial ranges. This has promoted further subdivision of paleoenvironmental research, making topics such as short-term climate events and rapid changes in paleoecological communities independent research directions.

With the application of big-data and artificial-intelligence technologies, stratigraphic data can be processed and analyzed rapidly, revealing more subtle geological phenomena and environmental changes. This data-driven subdivision enables paleoenvironmental research to locate problems more precisely and propose more targeted solutions.

The combined use of high-resolution sequence stratigraphy, biostratigraphy, chemostratigraphy, and other techniques provides a more comprehensive perspective for paleoenvironmental research. These methods complement one another in revealing high-frequency paleoenvironmental changes, paleoclimatic events, and paleocommunity succession, jointly forming an interdisciplinary framework for paleoenvironmental research.

Recent advances in stratigraphy have also promoted interdisciplinary integration with geology, geophysics, biology, chemistry, and other fields. For example, the combination of geology and biology has formed paleoecology, whereas the combination of geophysics and geology has promoted the development of new techniques such as seismic stratigraphy and sequence stratigraphy. This interdisciplinary integration has injected new vitality and innovative ideas into paleoenvironmental research.

3.2. How These Advances Have Changed Our Understanding of the Patterns of Paleoenvironmental Evolution

The application of high-precision chronological methods makes the temporal framework of paleoenvironmental evolution more accurate. Scientists can more precisely determine the timing of geological events and thereby reveal the staged characteristics and patterns of paleoenvironmental evolution.

The application of techniques such as high-resolution sequence stratigraphy and three-dimensional stratigraphic modeling clearly displays the spatial distribution characteristics of paleoenvironmental evolution. Scientists can more intuitively observe spatial changes in paleoenvironmental conditions during different geological periods, thereby revealing regional and global characteristics of paleoenvironmental evolution.

Recent stratigraphic advances have promoted the application of multifactor comprehensive analysis. Scientists no longer focus solely on a single geological phenomenon or environmental parameter, but instead consider multiple factors together in order to reveal the complexity and diversity of paleoenvironmental evolution.

3.3. Influence on Paleoclimatology, Paleoecology, Paleogeography, and Related Disciplines

Recent advances in stratigraphy provide paleoclimatological research with a more precise temporal framework and clearer spatial distribution characteristics. Scientists can reconstruct paleoclimate evolution more accurately and reveal the patterns and mechanisms of climate change.

The application of high-precision chronological methods and multidisciplinary integration techniques enables paleoecological research to extend to finer time scales and broader spatial ranges. Scientists can more comprehensively reveal the succession of paleocommunities and the patterns of ecological and environmental change.

Recent advances in stratigraphy have promoted the further development of paleogeographic research. Scientists can more accurately reconstruct the spatial distribution and evolutionary processes of paleogeographic environments, thereby revealing the patterns and mechanisms of geographic environmental change.

4. Advances in Stratigraphy Promoting Deeper and More Comprehensive Directions in Paleoenvironmental Research

Modern stratigraphy has not only expanded its research scope, but also deepened the understanding of stratigraphic types and their spatiotemporal distribution in relation to paleoenvironmental and paleotectonic conditions. This deepening enables researchers to reconstruct the historical evolution of paleoenvironmental conditions more precisely. For example, through sequence-stratigraphic research, scientists can use stratigraphic sequences composed of depositional systems and separated by discontinuity surfaces to subdivide and correlate strata, thereby revealing environmental information such as sea-level changes and climate changes during different periods of geological history.

With technological development, stratigraphy has introduced many new techniques and methods, such as seismic stratigraphy, ecostratigraphy, and event stratigraphy. The formation of these new fields and branches has greatly improved the accuracy and depth of stratigraphic research. For example, seismic stratigraphy uses seismic data to interpret stratigraphic structures and evolution, providing richer geological information for paleoenvironmental research. Ecostratigraphy integrates the study of paleobiological ecological environments, significantly improving the level of biostratigraphic research and further revealing the interaction between organisms and environments.

Event stratigraphy uses sudden global catastrophic events, such as global geomagnetic-field changes, sea-level changes, staged changes in the physicochemical conditions of the hydrosphere and atmosphere, and meteorite impacts, for stratigraphic correlation and the subdivision of stratigraphic boundaries. The global synchroneity of such events enables stratigraphic research to overcome regional limitations and achieve global stratigraphic correlation, thereby more comprehensively revealing the patterns of paleoenvironmental evolution. For example, by studying global sea-level changes, scientists can draw global sea-level curves and further predict the properties of subsurface rocks and sea-level conditions, providing important evidence for paleoenvironmental research.

The distinctive inland basin types in China, such as active continental-margin, rift, and foreland basins, provide important references for research on resource exploration in terrestrial faulted basins. By deeply investigating the sequence-stratigraphic characteristics of these basin types, scientists can better understand their formation and evolution and further reveal their paleoenvironmental characteristics. For example, in lacustrine basins, scientists use the theories and methods of sequence stratigraphy to reveal patterns of lake-level change and lacustrine depositional-environment evolution. These studies are of great significance for understanding the paleoenvironmental evolution of inland lakes [11, 10].

Magnetostratigraphy, as an important branch of stratigraphy, also plays an important role in paleoenvironmental research. Through magnetostratigraphic studies of geological records such as red clay, scientists can reveal their formation ages and paleoenvironmental information. For example, magnetostratigraphic studies of Miocene and Pliocene red clay have revealed its aeolian origin and evidence of fluvial modification in the Loess Plateau region, providing important clues for understanding the paleoclimate and paleoenvironment of this region [6,9].

5. Conclusions, Prospects, and Suggestions

5.1. Application Value and Influence of Recent Stratigraphic Advances in Paleoenvironmental Research

As an important branch of geology, stratigraphy has irreplaceable application value and broad influence in paleoenvironmental research. The following points summarize several key aspects of the application value and influence of recent stratigraphic advances in paleoenvironmental research.

By analyzing rocks, sediments, and the fossils and trace fossils contained in them from different geological periods, stratigraphy can reconstruct paleoclimatic information at high resolution. For example, China's loess-paleosol sequence is a natural archive of climate change and provides important materials for climate-change research.

Through methods such as rock-record analysis, chemical analysis of lake sediments, and ice-core records, stratigraphy can reveal the patterns and trends of Earth's climatic evolution and change, providing a scientific basis for predicting future climate change.

The interdisciplinary integration of stratigraphy with archaeology, environmental magnetism, environmental science, and other fields has promoted the in-depth development of paleoenvironmental research. For example, the rise of geoarchaeology has enabled more scientific identification of strata and relic accumulations during the excavation and study of archaeological sites, thereby allowing more accurate reconstruction of ancient human living environments and their changes [7].

Interdisciplinary integration not only enriches research methods, but also broadens research perspectives and promotes the sharing and transformation of research results.

The application of stratigraphy in paleoenvironmental research helps reveal the evolutionary history and future trends of environmental change, providing a scientific basis for environmental protection and resource utilization. By analyzing environmental characteristics in different geological periods, it is possible to assess current environmental conditions, predict environmental-change trends, and provide strong support for the formulation of environmental-protection policies [12].

5.2. Prospects for the Future Integration of Stratigraphy and Paleoenvironmental Research

In the future, the integration between stratigraphy and paleoenvironmental research will become more evident, mainly in the following aspects.

The interdisciplinary integration of stratigraphy with archaeology, environmental science, geology, geophysics, and other fields should be further strengthened to promote the development of cross-disciplinary research. By sharing research methods, data, and results, the common development of various disciplines can be promoted [13].

More new technologies and methods, such as remote sensing, LiDAR, microwave scattering, and meteorological satellites, should be introduced to improve the accuracy and reliability of stratigraphic and paleoenvironmental research. These new technologies will make data acquisition and processing more efficient, broaden the research scope, and deepen research outcomes.

Regional- and global-scale stratigraphic and paleoenvironmental research should be deepened to reveal the patterns and trends of environmental change across different regions and at the global scale. This will help achieve a more comprehensive understanding of the evolution of Earth's environmental system and provide a scientific basis for formulating global environmental-protection policies.

5.3. Possible Research Directions and Suggestions

Further research should focus on high-resolution climate records, such as high-resolution sedimentary and fossil records, in order to reveal climate-change information on shorter time scales. This will help improve the accuracy of predictions of future climate-change trends.

Paleoenvironmental reconstruction and simulation research should be strengthened. Computer simulation techniques can be used to reconstruct environmental conditions during different geological periods and to predict future environmental-change trends. This will help formulate more scientific and reasonable strategies for environmental protection and resource utilization.

Multidisciplinary collaborative research should be promoted by establishing interdisciplinary research teams to jointly carry out stratigraphic and paleoenvironmental studies. By sharing research resources and exchanging research results, research efficiency and quality can be improved.

Talent training and team building should be strengthened to cultivate more stratigraphic and paleoenvironmental researchers with interdisciplinary backgrounds and innovative abilities. Training courses, seminars, and other activities can be organized to improve researchers' professional competence and research ability.

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