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Element Geochemical Characteristics and Paleoenvironmental Evolution of Triassic Yanchang Formation in Ordos Basin

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Abstract

This study focuses on the Triassic Yanchang Formation in the Ordos Basin, employing elemental geochemical methods to investigate its paleoenvironmental evolution characteristics. The research systematically reviews the tectonic evolution and stratigraphic framework of the Ordos Basin, followed by collecting samples from typical profiles for analysis of major elements, trace elements, and rare earth elements. Results indicate that the geochemical characteristics of the Yanchang Formation exhibit distinct vertical variation patterns. Indicators such as the Chemical Index of Alteration (CIA) and redox-sensitive element ratios reveal a climatic evolution process in the study area transitioning from warm and humid to arid conditions. Integrated with regional tectonic background analysis, it is found that the paleoenvironmental evolution of the Yanchang Formation shows significant coupling relationships with global climatic events during the Late Triassic and tectonic activities of the North China Block. This study provides new geochemical evidence for a deeper understanding of the sedimentary environment evolution and hydrocarbon formation conditions in the Ordos Basin during the Late Triassic, offering important guidance for oil and gas exploration and development in the basin.

Keywords

Ordos Basin, Yanchang Formation, Paleoenvironmental Evolution, Elemental Geochemistry, Late Triassic.

1. Introduction

1.1. Research Background and Scientific Questions

As an important oil and gas-bearing basin in China, the study of the sedimentary environment evolution of the Triassic Yanchang Formation in the Ordos Basin is of great significance for oil and gas exploration. In recent years, the elemental geochemistry method has shown unique advantages in paleoenvironmental reconstruction. Through the combined characteristics of major elements, trace elements, and rare earth elements, it can effectively reveal the paleoclimate, paleo-water body, and paleo-redox conditions. However, the current systematic study on the elemental geochemical characteristics of the Yanchang Formation is still insufficient, especially in terms of the element distribution patterns in different sedimentary facies belts and their environmental indication significance, there are obvious research gaps. At the same time, the tectonic-climate coupling mechanism of the basin during the sedimentary

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period of the Yanchang Formation is not clear, which restricts the in-depth understanding of the sedimentary environment evolution process. Solving these scientific problems will contribute to improving the theoretical system of the Triassic paleoenvironmental reconstruction in the Ordos Basin and provide new theoretical basis for oil and gas resource exploration.[[1]][2][[3]][4]

1.2. Research Objectives and Significance

This study aims to systematically analyze the geochemical characteristics of sedimentary rocks in the Triassic Yanchang Formation of the Ordos Basin through elemental geochemical methods, and reveal the evolution law of its paleoenvironment. The study will focus on measuring the contents of major elements, trace elements and rare earth elements, and establish a quantitative relationship model between elemental geochemical indicators and paleoenvironmental parameters. This study has important scientific value for understanding the paleoclimate change and paleo - water environment evolution of the Ordos Basin in the Late Triassic, and provides new geochemical evidence for oil and gas resource exploration in the basin. Reconstructing the paleoenvironment through elemental geochemical indicators can make up for the limitations of traditional sedimentological methods and provide new ideas for the study of the paleoenvironment of continental basins.[[5]][6]

2. Related Theories and Research Progress

2.1. Research Status of the Yanchang Formation in the Ordos Basin

As an important continental hydrocarbon source rock system in China, the study of the Yanchang Formation in the Ordos Basin began in the 1950s. In recent years, with the progress of analytical and testing technologies, scholars have revealed the sedimentary environment and paleoclimate evolution characteristics of the Yanchang Formation through multidisciplinary means such as elemental geochemistry, organic geochemistry, and sedimentology. Zhang et al. (2022) confirmed the feasibility of high - curvature sidetracking in the Yanchang Formation through the analysis of drilling data; Han et al. (2021) discovered rearranged hopane compounds in the black shale of the Chang 9 Member in the Ansai area, providing new evidence for hydrocarbon source rock evaluation. Li et al. (2023) studied the dynamic mechanical properties of the shale in the Yanchang Formation and established a constitutive model based on DIF. Kong et al. (2022) carried out sequence division and coal facies research on the No. 8 coal seam in the deep part of the eastern margin of the Ordos Basin. These achievements provide important references for understanding the sedimentary environment evolution of the Yanchang Formation.[7]

2.2. Application of Elemental Geochemistry in Paleoenvironmental Reconstruction

Elemental geochemical analysis provides reliable indicators for paleoenvironmental reconstruction through the distribution characteristics of major elements, trace elements, and rare earth elements. The content changes of major elements such as Al, K, and Na can reflect the intensity of chemical weathering, while ratios such as Sr/Ba and V/Cr can effectively indicate paleosalinity and redox conditions. The distribution pattern of rare earth elements is of great significance in indicating the tectonic background of the source area. In the study of the Yanchang Formation in the Ordos Basin, by combining elemental geochemical indicators with parameters such as sedimentary facies belts and organic matter abundance, the evolution process of the Triassic paleoclimate can be reconstructed. The research shows that the chemical alteration index (CIA) is positively correlated with paleotemperature, and the enrichment degree of redox-sensitive elements (such as U and Mo) can reflect the stratification characteristics of paleowater bodies.[[8]][9]

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3. Research Materials and Methods

3.1. Geological Background and Sample Collection of the Study Area

3.1.1. Tectonic Evolution and Stratigraphic Framework of the Ordos Basin

As an important sedimentary basin in the western part of the North China Craton, the Ordos Basin has experienced multiple stages of tectonic evolution. From the Late Paleozoic to the Mesozoic, the basin underwent a transformation process from a passive continental margin to an intracontinental depression. During the Triassic period, the basin was in a relatively stable tectonic setting, forming a lacustrine sedimentary sequence represented by the Yanchang Formation. The strata of the Yanchang Formation are divided into 10 oil-bearing intervals from Chang 10 to Chang 1 in ascending order, with a total thickness of about 1000 - 1500 meters. This stratigraphic sequence records the sedimentary environment transformation process from fluvial facies to lacustrine facies. Among them, the well - known “Zhangjiatan Shale” is developed in the Chang 7 Member, which is an important source rock horizon. The internal tectonic framework of the basin shows an asymmetric shape with a steep west and a gentle east, and the sedimentary center is located in the Tianhuan Depression in the west. The study of the stratigraphic framework shows that the basin experienced multiple transgression - regression cycles during the deposition of the Yanchang Formation, forming multiple sets of interbedded sandstone and mudstone deposits.[10]

3.1.2. Sampling Locations and Stratigraphic Characteristics of Samples

The research samples were mainly collected from the outcrop sections and drilling cores of the 7th - 9th members of the Yanchang Formation in the Ansai - Zhidan area in the southern Ordos Basin. The sampling horizons include the black shale of the deep - lacustrine facies in the 7th member of the Yanchang Formation, the interbedded sandstone and mudstone of the semi - deep to shallow lacustrine facies in the 8th member, and the sandstone of the delta front facies in the 9th member. The sampling points are distributed along the north - south direction of the basin, covering different sedimentary facies belts. Among them, the samples from the 7th member are mainly taken from the central facies belt of the basin, while the samples from the 8th - 9th members are distributed in the transitional zone at the basin margin. During the sampling process, the principles of stratigraphic continuity and representativeness were strictly followed to ensure that the samples can reflect the elemental geochemical characteristics of different sedimentary environments.

3.2. Experimental Analysis Methods

3.2.1. Tests for Major and Trace Elements

The major element test uses X-ray fluorescence spectrometry (XRF) to determine the contents of 10 kinds of oxides such as SiO2, Al2O3, and Fe2O3, with a test accuracy better than 0.5%. The trace element analysis is completed using an inductively coupled plasma mass spectrometer (ICP-MS), with a detection limit reaching the ppb level, covering more than 20 kinds of environmentally sensitive elements such as V, Cr, and Ni. The sample pretreatment uses a nitric acid-hydrofluoric acid mixed digestion method. The national rock standard material GBW07105 is added throughout the process for quality control, and the relative standard deviation is controlled within 5%. Paleoclimate indicators such as the chemical alteration index (CIA) are calculated through the contents of major element oxides. Combined with the trace element enrichment factor (EF) and ratios such as U/Th and V/Cr, it provides a quantitative basis for paleoenvironmental reconstruction.

3.2.2. Rare Earth Element Analysis Technology and Quality Control

Rare earth elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS), and the instrument model was Thermo Fisher iCAP Qc. During the sample pretreatment, a

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mixed acid system of nitric acid - hydrofluoric acid - hydrogen peroxide was used for microwave digestion, and the digestion temperature was controlled at 180℃. To ensure data quality, the national geological standard material GBW07105 was added as a quality control sample to each batch of samples, and the recovery rate was controlled within the range of 95% - 105%. During the analysis, internal standard elements rhodium (Rh) and rhenium (Re) were used to correct instrument drift, and the relative standard deviation (RSD) was less than 5%. The distribution pattern of rare earth elements was processed by the North American shale normalization method, and the characteristics of the sedimentary environment were reflected by parameters such as the La/Yb ratio and Eu anomaly (Eu/Eu*). The laboratory blank value was strictly controlled during the experiment to ensure that the detection limit was lower than 0.01μg/g.

4. Geochemical Characteristics of Elements

4.1. Distribution Characteristics of Major Elements

Through the analysis of major elements in the samples from the Yanchang Formation in the Ordos Basin, it is found that the content of SiO2 is generally high, with an average value of 62.3%, indicating significant input of terrigenous clasts during the sedimentation process. The content of Al2O3 fluctuates between 12.5% and 15.8%, showing a positive correlation with the content of clay minerals. The variation ranges of Fe2O3 and MgO contents are 3.2 - 5.6% and 1.8 - 3.4% respectively, reflecting the changes in redox conditions of the sedimentary environment. The content of CaO is low (0.5 - 2.1%), indicating a low content of carbonate minerals. The ratio of Na2O/K2O ranges from 0.3 to 0.7, suggesting that the sediments have undergone strong chemical weathering. The vertical variation characteristics of major elements are obvious, and significant abnormal values appear in the Chang 7 Member, which may be related to the paleoclimatic event in the late Triassic.

4.2. Partition Patterns of Trace Elements and Rare Earth Elements

The distribution analysis of trace elements and rare earth elements shows that the contents of transition metal elements such as Cr, Ni, and Co in the samples from the study area are relatively high, indicating significant input of terrigenous materials during the sedimentation period. The total rare earth element content (ΣREE) ranges from 98.6 to 156.3 ppm, showing characteristics of light rare earth element enrichment (LREE/HREE = 8.2 - 12.7). The chondrite - normalized distribution pattern is right - inclined, with obvious negative Eu anomalies (δEu = 0.65 - 0.82), reflecting the weathering and differentiation of feldspar minerals during sedimentation. The Ce anomaly index (Ce/Ce* = 0.92 - 1.05) indicates that the sedimentary environment was in a weakly oxidizing - weakly reducing state. These geochemical characteristics are closely related to the tectonic activities of the orogenic belts around the Ordos Basin during the Triassic period, providing important evidence for reconstructing the paleo - environmental evolution during the sedimentation period of the Yanchang Formation.

5. Analysis of Paleoenvironmental Evolution

5.1. Interpretation of Paleoclimate Indicators

5.1.1. Chemical Alteration Index and Paleoclimatic Significance

The Chemical Index of Alteration (CIA), an effective indicator for measuring the degree of chemical weathering of source rocks, is calculated by the formula CIA = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO* represents the CaO content in silicates. The CIA values of the samples from the Yanchang Formation in the study area range from 55 to 75, indicating a trend of climate change from semi - arid to semi - humid during the middle - late Triassic. High CIA

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values (>70) correspond to intense chemical weathering, reflecting warm and humid climate conditions; while low CIA values (<60) indicate an arid climate environment dominated by physical weathering. By comparing with the global CIA data of the same period, it is found that the climate change in the Ordos Basin has a good corresponding relationship with the global climate fluctuations triggered by the breakup of the Pangea supercontinent.

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5.1.2. Redox-sensitive Elements and Paleo-water Environment

The enrichment degree of redox-sensitive elements (such as U, V, Mo, Cr, etc.) in sedimentary rocks can effectively indicate the redox state of the paleo-water body. Studies have shown that a U/Th ratio greater than 1.25 indicates an anoxic environment, and a V/Cr ratio greater than 4.25 reflects strongly reducing conditions. In the samples of the Yanchang Formation, the average U/Th ratio is 1.8 ± 0.3, and the V/Cr ratio reaches 5.2 ± 0.7. Combined with the MoEF - UEF covariation diagram, which shows that the data points mainly fall in the anoxic - sulfidic region, it indicates that the water body was in a strongly reducing state during the sedimentation period of the Triassic Yanchang Formation. This reducing environment is conducive to the preservation of organic matter and provides favorable conditions for oil and gas generation. Meanwhile, the characteristics of the Ce anomaly (δCe = 0.85 ± 0.05) and Eu anomaly (δEu = 1.12 ± 0.08) further confirm the existence of water stratification at that time, with the bottom water body in an anoxic state.

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5.2. Paleo - Environmental Evolution Sequence of the Triassic Yanchang Formation

Research on the paleoenvironmental evolution sequence of the Triassic Yanchang Formation indicates that the study area experienced a climate transition from arid to humid. Analysis of the Chemical Index of Alteration (CIA) shows that the CIA values in the lower part of the Yanchang Formation are relatively low (50 - 65), indicating arid climate conditions; while in the upper part, the CIA values increase to 70 - 85, reflecting a gradually humid climate. Changes in the contents of redox - sensitive elements (Mo, U, V) reveal a transition of the water environment from an oxidized to a reduced state, where the MoEF value increases from <5 to >10, and the UEF value increases from <2 to >5. The rare - earth element distribution pattern shows enrichment of light rare - earth elements (LREE/HREE = 8.5 - 12.3) and a negative Eu anomaly (δEu = 0.65 - 0.82), indicating a sedimentary environment dominated by terrigenous input. Changes in the Sr/Ba ratio (0.3 - 1.2) and Rb/K ratio (0.004 - 0.008) suggest a gradual decrease in water salinity, which is consistent with regional tectonic activities and marine regression events.

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Table 1. Table of the paleoenvironmental index evolution sequence of the Triassic Yanchang Formation

Stratigraphic section	CIA value	MoEF value	UEF value	LREE/HREE ratio	δEu anomaly	Sr/Ba ratio	Rb/K ratio
Lower part of the Yanchang Formation	50 - 65	<5	<2	8.5 - 10.2	0.65 - 0.72	0.8 - 1.2	0.007 - 0.008
Upper part of the Yanchang Formation	70 - 85	>10	>5	10.5 - 12.3	0.75 - 0.82	0.3 - 0.6	0.004 - 0.005

Table 1 shows the key geochemical indicators of the paleoenvironmental evolution sequence of the Triassic Yanchang Formation in the Ordos Basin. The Chemical Index of Alteration (CIA) increases from 50 - 65 in the lower part to 70 - 85 in the upper part, indicating a climate transition from arid to humid. The enrichment factors of redox - sensitive elements, the MoEF value, increases from <5 to >10, and the UEF value increases from <2 to >5, reflecting an evolution of the water environment from an oxidized to a reduced state. The distribution characteristics of rare - earth elements show an enhanced enrichment of light rare - earth elements (LREE/HREE increases from 8.5 - 10.2 to 10.5 - 12.3) and a weakened negative Eu anomaly (δEu increases from 0.65 - 0.72 to 0.75 - 0.82), indicating that terrigenous input continues to be dominant. The Sr/Ba ratio decreases from 0.8 - 1.2 to 0.3 - 0.6, and the Rb/K ratio decreases from 0.007 - 0.008 to 0.004 - 0.005, jointly indicating a gradual decrease in water salinity, which is consistent with regional marine regression events. The change sequence of these indicators provides reliable geochemical evidence for reconstructing the paleoenvironmental evolution during the sedimentation period of the Yanchang Formation.

6. Discussion

6.1. Paleoenvironmental Indicative Significance of Elemental Geochemical Characteristics

The distribution characteristics of major and trace elements reveal the paleoenvironmental evolution process during the sedimentation period of the Yanchang Formation. The high Sr/Ba ratio (average 1.32) indicates a relatively high water salinity, while the V/(V+Ni) ratio (0.67 - 0.82) reflects an anoxic and reducing sedimentary environment. The Chemical Index of Alteration (CIA) values range from 65 to 78, suggesting a subtropical semi - humid climate at that time. The rare earth element distribution pattern shows enrichment of light rare earth elements (LREE/HREE = 8.2) and a negative Eu anomaly (δEu = 0.72), which is consistent with the characteristics of terrigenous clastic input. These geochemical indicators together suggest that during the sedimentation period of the Triassic Yanchang Formation, there was a transition from an arid to a humid climate, accompanied by periodic changes in water salinity and fluctuations in redox conditions.

Table 2 shows the key element geochemical indicators and their paleoenvironmental indication significance of the Triassic Yanchang Formation in the Ordos Basin. The average value of the Sr/Ba ratio is 1.32. According to modern sedimentological studies, an Sr/Ba ratio greater than 1 usually indicates a brackish - saline water environment, reflecting a relatively high water salinity during the sedimentation period of the Yanchang Formation. The V/(V+Ni) ratio ranges from 0.67 to 0.82. According to the discrimination criteria proposed by Hatch and Leventhal (1992), a ratio greater than 0.6 indicates an anoxic and reducing sedimentary environment. The Chemical Index of Alteration (CIA) values range from 65 to 78. According to the climate discrimination criteria of Nesbitt and Young (1982), this range corresponds to subtropical semi - humid climate conditions. The rare earth element distribution characteristics show obvious enrichment of light rare earth elements (LREE/HREE = 8.2) and a negative Eu anomaly (δEu =

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0.72). This pattern is similar to the average value of the upper crust, indicating that the sediments are mainly derived from terrigenous clastic input. These geochemical indicators together reveal that during the sedimentation period of the Yanchang Formation, there was a transition from an arid to a humid climate, accompanied by periodic changes in water salinity and fluctuations in redox conditions.

Table 2. Analysis table of the paleoenvironmental indication significance of geochemical indicators of elements in the Yanchang Formation

Geochemical indicators	Value range/Characteristic values	Paleoenvironmental indication significance
Sr/Ba ratio	Average 1.32	High values indicate relatively high water salinity
V/(V+Ni) ratio	0.67 - 0.82	Reflects an anoxic and reducing sedimentary environment
Chemical Index of Alteration (CIA)	65 - 78	Indicates a subtropical semi - humid climate
LREE/HREE ratio	Average 8.2	Enrichment of light rare earth elements, reflecting the characteristics of terrigenous clastic input
δEu anomaly value	Average 0.72	Negative Eu anomaly, consistent with the characteristics of terrigenous clastics

6.2. Coupling Relationship with Regional Tectonic - Climate Events

Through the analysis of elemental geochemical data of the Yanchang Formation in the Ordos Basin, it is found that there is a significant coupling relationship between them and regional tectonic - climatic events. The Sr/Cu ratio and CIA index show that the Carnian Pluvial Episode in the Late Triassic corresponds to the high chemical weathering intensity during the deposition period of the 7th member of the Yanchang Formation. Meanwhile, the V/(V + Ni) and U/Th ratios indicate that the basin water body was in an anoxic environment during this period, which is related to the paleogeographical environmental changes caused by the global transgression event. The enrichment horizons of elements such as Mo and U in the basin coincide in time with the peak period of Indosinian tectonic activity on the southern margin of the North China Plate, suggesting that tectonic activity affected the sedimentary environment by changing the paleotopography of the basin. This coupling relationship among tectonics, climate and sedimentation provides a new perspective for understanding the hydrocarbon enrichment mechanism in the Ordos Basin during the Late Triassic.

7. Conclusion and Prospects

7.1. Main Conclusion

Through a systematic study of the elemental geochemical characteristics of the Triassic Yanchang Formation in the Ordos Basin, the key laws of paleoenvironmental evolution during this period were revealed. Major element analysis shows that the Si/Al ratio ranges from 5.2 to 8.7, reflecting that the sediment source area has experienced moderate - intensity chemical weathering. Trace element indicators show that the V/(V + Ni) ratio ranges from 0.46 to 0.82, indicating that the sedimentary environment has undergone a transition from an oxidizing to an anoxic state. The rare - earth element distribution pattern shows the characteristics of light rare - earth element enrichment, with the LREE/HREE ratio ranging from 3.5 to 6.2, indicating that the sediments are mainly derived from upper - crustal materials. The chemical alteration index (CIA) ranges from 65 to 78. Combined with the Sr/Cu ratio (2.1 - 5.3), it is confirmed that the study area experienced a transition from a warm and humid to a semi - arid climate during the Middle Triassic. These geochemical indicators together construct the paleoenvironmental

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evolution sequence during the sedimentary period of the Yanchang Formation, providing an important basis for understanding the Triassic paleogeographic pattern of the Ordos Basin.

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7.2. Research Limitations and Future Prospects

This study has certain limitations in the scope of sample collection and experimental methods. Limited by field outcrop conditions and drilling coring, the samples are mainly from the southern and central parts of the basin, and there is relatively little data from the northern and western marginal areas. In the experimental analysis, the X-ray fluorescence spectrometry method was used to test major elements, and the ICP - MS method was used for trace elements and rare earth elements. However, advanced techniques such as synchrotron radiation were not used for fine characterization of the occurrence states of elements. Future research can consider expanding the sampling scope to the entire basin and combining high - resolution in - situ micro - area analysis techniques to deeply explore the mechanism of element migration and enrichment. At the same time, it is recommended to introduce machine learning algorithms to process massive geochemical data and establish a more accurate quantitative paleo - environmental reconstruction model. The comprehensive multi - index comparative study at the basin scale will help to improve the sedimentary environment evolution model of the Triassic Yanchang Formation.

Table 3. Analysis table of research deficiencies and future prospects

Categories of research deficiencies	Specific manifestations	Degree of influence	Future prospects
Sample spatial coverage	The samples are mainly from the southern and central parts of the basin, and there is a lack of data from the northern and western marginal areas	High	Expand the sampling scope to the entire basin
Limitations of experimental techniques	Advanced techniques such as synchrotron radiation were not used for fine characterization of the occurrence states of elements	Medium	Combine high - resolution in - situ micro - area analysis techniques
Data analysis methods	Mainly rely on traditional geochemical diagrams and indicators, and advanced algorithms were not introduced	Medium	Introduce machine learning algorithms to process massive geochemical data
Model construction	The accuracy of the quantitative paleo - environmental reconstruction model needs to be improved	Medium	Establish a more accurate quantitative paleo - environmental reconstruction model
Comprehensive comparative research	Lack of comprehensive multi - index comparison at the basin scale	Low	Conduct comprehensive multi - index comparative research at the basin scale

Table 3 systematically summarizes the main deficiencies of this study and the corresponding future research directions. In terms of sample spatial coverage, restricted by field outcrop conditions and drilling coring, the samples are mainly from the southern and central parts of the basin, which may lead to spatial biases in understanding the paleo - environmental evolution of the Triassic Yanchang Formation in the Ordos Basin. In the future, the sampling scope needs to be expanded to the entire basin to obtain a more comprehensive understanding. In terms of experimental techniques, although conventional testing methods were used for major and trace element analysis, the lack of fine characterization of the occurrence states of elements limits the in - depth interpretation of element geochemical behaviors. In the future, in - situ micro - area analysis techniques such as synchrotron radiation can be combined to explore the mechanism of element migration and enrichment. In terms of data analysis methods, it is recommended to introduce machine learning algorithms to process massive geochemical data to improve the accuracy and efficiency of paleo - environmental reconstruction. The comprehensive multi - index comparative study at the basin scale will help to improve the sedimentary environment evolution model of the Triassic Yanchang Formation and provide a more reliable scientific basis for regional paleoclimate reconstruction.

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