

A Review of Research Frontiers and Advances in Continental Sequence Stratigraphy

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ABSTRACT

Sequence stratigraphy not only provides an isochronous stratigraphic framework for basin analysis, but also offers an important integrated geological framework for sedimentary paleogeographic reconstruction and the exploration and development of sedimentary mineral resources. Over the past three decades, sequence stratigraphy has continued to develop in terms of theoretical systems, sequence architecture, integrated interpretation of multiple datasets, and applications in energy exploration. Significant progress has been made particularly in the controlling factors of sequence formation in continental basins, sequence-stratigraphic architecture of faulted, depressed, and foreland lacustrine basins, the distribution patterns of sand bodies, and research methods for sequence stratigraphy in continental lacustrine basins. Compared with marine basins, continental lacustrine basins are jointly controlled by tectonic activity, climatic change, lake-level fluctuation, proximal and multiple sediment supplies, and rapid changes in sedimentary facies; therefore, their sequence composition and stratigraphic stacking patterns are more complex. Future research on continental sequence stratigraphy should further focus on sequence architecture in different types of basins, standardization of research terminology and workflows, relationships between sequences and source-to-sink systems, relationships between sequences and shoreline-migration trajectories, stratigraphic stacking patterns and sedimentary responses, deep-water sequence stratigraphy, and numerical simulation of sequence architecture, so as to better serve the exploration and development of energy resources.

KEYWORDS

Sequence Stratigraphy; Research Progress; Sequence Architecture; Sand-Body Distribution.

1. INTRODUCTION

Sequence stratigraphy is an important branch of geology that studies the sedimentary responses to base-level changes, the origin of sedimentary-basin filling, internal basin architecture, and the relationships between accommodation space and sedimentation. This discipline has strong integrative and applied value in studies of stratigraphic-unit division, spatio-temporal distribution of depositional systems, and prediction of sedimentary mineral resources in global or regional sedimentary basins. It has therefore received broad attention in both academic research and the exploration and development of sedimentary mineral resources [4,7,8].

The development of sequence stratigraphy can be divided broadly into four stages. The first stage was the conceptual germination period (1949-1976), represented by the concept of a “sequence” bounded by unconformities proposed by Sloss [15]. The second stage was the development period of seismic stratigraphy (1977-1987), marked by the establishment of seismic stratigraphy by Vail [16], during which the controlling role of sea-level change in the formation of depositional sequences was emphasized. The third stage was the formation and development period of sequence stratigraphy

(1988-2008). During this period, the classical sequence stratigraphy established by Van Wagoner [17], the genetic sequence stratigraphy proposed by Galloway [14], the transgressive-regressive cyclic sequence stratigraphy developed by Embry and Johannessen [13], and the high-resolution sequence stratigraphy founded by Cross [12] jointly promoted the improvement of the theoretical system of sequence stratigraphy. The fourth stage is the integrated development period of sequence stratigraphy (from 2009 to the present), represented by the standardization of sequence stratigraphy and the proposal of multiple types of sequence architecture by Catuneanu [11]. Since then, sequence stratigraphy has gradually entered a stage characterized by conceptual standardization, procedural normalization, and integrated interpretation of multiple datasets.

The basic principles of sequence stratigraphy are applicable to isochronous stratigraphic correlation and depositional-system analysis in sedimentary basins of different scales and types. It should be noted that, although existing mainstream sequence architectures have good explanatory power in specific geological settings, no single sequence architecture can be applied to all sedimentary basins and all sedimentary records [11]. pointed out that different sequence-stratigraphic architectures are based on particular geological features and interpretive objectives, and that the positions of sequence boundaries and the division of systems tracts may differ significantly. Therefore, the development of sequence stratigraphy requires further standardization of basic concepts, sequence boundaries, systems-tract division, and interpretive procedures while retaining the applicability of different architectural schemes.

2. THEORETICAL BASIS AND BASIN TYPES OF CONTINENTAL SEQUENCE STRATIGRAPHY

Continental-basin sequence stratigraphy is a research field in which Chinese scholars have made important contributions to the international theoretical and methodological system of sequence stratigraphy. Its research objects include a variety of continental depositional systems, such as alluvial fans, rivers, deltas, beach bars, lakes, and deep-water deposits. The core issue is to clarify the mechanisms of sequence formation and the characteristics of stratigraphic architecture in continental basins.

Previous studies have shown that the basic principles and methods of marine sequence stratigraphy, which originated from passive continental-margin basins, can be applied to the study of sequence stratigraphy in continental lacustrine basins under certain conditions [4,7,8,10,11]. The main reason is that allocyclic sedimentation in continental depositional environments such as lakes has certain similarities to marine sedimentation controlled by relative sea-level change. However, continental lacustrine basins differ significantly from marine sedimentary basins in geological setting. These differences are mainly reflected in the strong influence of tectonic activity and climatic change, complex basin types and structures, relatively small lake-water bodies, prominent proximal and multiple-source sediment supply, frequent lake-level fluctuations, diverse depositional systems with rapid facies changes, and the lack of stable and continuous topographic breaks in many lacustrine basins. Therefore, sea-level curves cannot be directly used as the basis for sequence division in continental lacustrine basins. The key factors controlling sequence architecture in continental basins are mainly tectonic activity, climatic change, base-level fluctuation, and sediment supply.

The dynamic mechanisms of sequence formation in continental basins are mainly related to regional tectonic stress fields, episodic tectonic activity, lithospheric extension or flexure, climatic cycles, and lake-level changes. These factors jointly control changes in accommodation space, sediment-supply intensity, and the migration directions of depositional systems, thereby determining the formation and stacking patterns of sequences of different orders [2]. Therefore, when sequence-stratigraphic theory is applied to continental basins, tectonic activity, climatic change, paleogeomorphology, base level, and provenance conditions must be considered comprehensively, and sequence-stratigraphic architectures that reflect the geological characteristics of continental basins should be established.

Chinese continental lacustrine basins mainly developed during the Mesozoic-Cenozoic. After the Indosinian movement, the Paleozoic east-west tectonic framework of the Chinese continental blocks was adjusted under the influence of multidirectional tectonic forces, including the westward push of the Pacific Plate, the northward push of the Indian Plate, and the southward push of the Siberian Plate. As a result, sedimentary basins with distinct differences in scale and structure were formed. According to their formation mechanisms, Chinese continental basins can be broadly divided into extensional basins, flexural basins, and strike-slip-extensional basins [1].

Extensional basins formed in the setting of lithospheric stretching and thinning, and were mainly controlled by deep mantle dynamics and regional extensional tectonics. Such basins are mainly distributed in eastern China and adjacent offshore areas, including large rift basins such as the Songliao Basin and Bohai Bay Basin, as well as smaller faulted basin groups such as the Erlian and Hailar basin groups. Extensional basins are commonly bounded by normal faults, experienced multiple stages of tectonic evolution during the Yanshanian and Himalayan periods, and developed a distinct “faulted-depressed” two-layer structure. Differential activity of normal faults within these basins resulted in marked differences in depositional conditions among steep-slope belts, gentle-slope belts, and central deep-sag belts. Slope-break zones formed by synsedimentary faults exerted important control over sediment-transport pathways and sand-body distribution.

Flexural basins are mainly distributed in central and western China, including the Junggar, Tarim, Sichuan, and Ordos basins. The Mesozoic-Cenozoic evolution of these basins was closely related to the activities of adjacent orogenic belts. Orogenic uplift, compressional thrusting, and loading jointly promoted the formation of foreland-style depressions. For example, during the Late Triassic foreland filling of the southwestern Ordos Basin, alternating intensities of tectonic activity controlled the sediment-filling rate and the progradation or retreat of clastic depositional systems toward the lake basin, thereby forming cyclic sequence-stratigraphic successions. After the development of foreland basins, weakened flexure could further lead to the formation of large, gently sloping depressions with relatively stable tectonic conditions, in which shallow inland lakes and surrounding delta systems developed.

Strike-slip-extensional basins commonly have elongated geometries and develop directly near strike-slip fault zones, such as the Baise Basin in Guangxi and the Yishu faulted basin in Jilin. The subsidence and filling processes of these basins are controlled jointly by extension and strike-slip movement. They commonly show asymmetric sedimentary filling on the two sides of faults, axial migration of depocenters, and local enhancement of pull-apart subsidence. It should be noted that the genetic classification of Chinese continental basins has not yet been fully unified. Some studies classify sedimentary basins into three categories: compressional or foreland basins, extensional basins, and transitional basins. Among them, the Tarim, Junggar, and Qaidam basins are commonly classified as compressional basins; the Songliao, Bohai Bay, and Pearl River Mouth basins are mostly classified as extensional basins; and the Sichuan and Ordos basins show certain transitional characteristics [1,6,9].

3. RESEARCH STATUS AND ADVANCES IN SEQUENCE STRATIGRAPHY OF CONTINENTAL LACUSTRINE BASINS

Complex tectonic frameworks, episodic tectonism, and climatic variations at different frequencies jointly lead to diverse sequence architectures and complex sequence compositions in continental sedimentary basins. Compared with climatic change, tectonism usually exerts a stronger and broader influence on sequence formation in continental lacustrine basins, and is the primary controlling factor of sequence development. In general, low-frequency lacustrine sequences and low-frequency systems tracts are mainly controlled by tectonic-subsidence cycles, whereas high-frequency sequences and high-frequency systems-tract cycles are mainly influenced by changes in the relationship between

evaporation and precipitation under climatic control. Relative lake-level change is the integrated result of tectonic subsidence, climatic change, sediment supply, and other factors.

The main controlling factors of sequence formation in continental lacustrine basins differ markedly from those in marine basins. Sequence development in continental basins is mainly controlled by tectonic movement, climatic change, sediment supply, and lake-level fluctuation. Tectonic subsidence creates accommodation space and provides sites for sediment accumulation, whereas tectonic uplift may cause strata to deform and be eroded, forming unconformities as sequence boundaries. Paleoclimatic conditions mainly affect sediment types and lake-water conditions, and cause short-period fluctuations in accommodation space through changes in precipitation and evaporation. Sediment supply determines the rate at which accommodation is consumed, and has an important influence on sand-body scale, depositional-facies distribution, and stratigraphic stacking patterns.

In continental lacustrine basins, regional tectonic movements control the formation of first-order, second-order, and some third-order sequences, and the style of tectonic activity has a clear influence on sequence architecture. Different activity patterns of boundary faults in faulted basins can produce different processes of accommodation-space change, which, together with sediment supply, control sequence architecture. Extensional fault activity may appear as one episode of strong faulting, synsedimentary faulting, or multiphase faulting, which respectively form different sequence styles such as simple fault-depression sequences, synsedimentary fault-depression sequences, and multiphase fault-depression sequences [3].

In closed lacustrine basins, lake level is commonly lower than the regional base level, and relative lake-level change responds relatively weakly to overall tectonic subsidence and is more strongly affected by climatic factors. In open lacustrine basins, climatic change not only affects lake-level rise and fall, but also controls sediment-supply volume and depositional-facies types. When the sediment-supply rate is greater than the tectonic-subsidence rate of the basin basement, a contractional systems tract is more likely to form; when the sediment-supply rate is lower than the tectonic-subsidence rate, an expansion systems tract is more likely to develop.

Compared with marine basins, the study of sequence stratigraphy in continental lacustrine basins places greater emphasis on integrated verification using multiple datasets, scales, and methods. Commonly used data include outcrops, drilling, well logging, seismic data, paleontological data, geochemical data, and physical or numerical simulations. Outcrop data are intuitive and detailed, and can be used to identify key sequence boundaries, systems tracts, and depositional-system associations, making them an important basis for establishing high-resolution sequence frameworks. Drilling and well-log data have the advantages of good vertical continuity and relatively high resolution, and can be used to finely interpret parasequence-set stacking patterns. Seismic data have broad coverage and strong spatial continuity; sequence boundaries can be identified by reflection-termination patterns, and interpretation accuracy can be improved through well-seismic calibration. Paleontological data provide evidence for sequence dating, depositional-environment reconstruction, and key-boundary identification. Geochemical data can assist in recognizing depositional-environment changes and sequence boundaries through indicators such as total organic carbon, stable isotopes, and trace elements. Physical and numerical simulations can quantitatively characterize basin subsidence, lake-level change, provenance supply, and sediment compaction, providing new approaches for revealing sequence-stratigraphic frameworks and the evolution of depositional facies belts [3,5].

4. CONCLUSIONS

Overall, although sequence stratigraphy has a relatively short history of formation and development, it has become an important theoretical and methodological system for sedimentary-basin analysis and prediction of sedimentary mineral resources. Continental sequence stratigraphy has been widely

applied to various types of continental basins in China, and has produced research achievements with distinctive continental-basin characteristics in terms of controlling factors of sequence formation, sequence architecture, sand-body distribution prediction, and integrated data interpretation.

Future research on continental sequence stratigraphy may focus on the following directions. First, the concepts, terminology, research procedures, and interpretation standards of sequence stratigraphy should be further normalized. Second, sequence-stratigraphic architecture and its formation mechanisms in different types of sedimentary basins should be investigated. Third, the coupling relationships among tectonic activity, climatic change, lake-level fluctuation, and sediment supply should be strengthened. Fourth, the response relationships among sequences, source-to-sink systems, shoreline-migration trajectories, and stratigraphic stacking patterns should be clarified. Fifth, research on deep-water sequence stratigraphy, sequence architecture of fine-grained deposits, and applications to unconventional oil and gas exploration should be promoted. Sixth, quantitative sequence stratigraphy and numerical simulation based on three-dimensional visualization, big data, and artificial intelligence should be developed. Through the deepening of these research directions, continental sequence stratigraphy will play a greater role in sedimentary-basin analysis, sand-body prediction, and the exploration and development of energy resources.

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