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Study on sequence stratigraphy from Benxi to Taiyuan formation in Northeastern Ordos Basin

Shen Yu-lin, Guo Ying-hai, Jing Hai-xia, Xie Tao, Gao Zhen-jun, Zhang Xiao-bo*

School of Resources and Earth Science, China University of Mining and Technology, Xuzhou 221008, China

Abstract

Based on the study of the vertical sedimentary sequence, we recognize the assemblage of vertical lithology, the geochemical test result of mudstone sample, and the characteristics of logs, the sequence stratigraphic interfaces such as regional unconformity, regional tectonic regime interface, sedimentary system interface, transgression surface and so on. Benxi to Taiyuan formation formed in the epicontinental sea, which has subdued floor, so most of the sequence structures from Benxi to Taiyuan formation are duality system tract. Tectonic disturbance, sea level change, and differential compaction provide enough accommodation space for distribution of K1 sandstone and Qiaotou sandstone. At last we establish the framework and model of sequence stratigraphy from Benxi to Taiyuan formation in northeastern Ordos basin in this paper, which contains type model of ramp marginal basin and type of ramp in epicontinental sea background.

Keywords: sequence stratigraphy; epicontinental sea; Qiaotou sandstone; Northeastern Ordos basin

Since the special publication No. 42 of SEPM [1] introduced new concepts and principles of sequence stratigraphy, a large number of stratigraphic studies in sedimentary basins have shown a recurring pattern of sequence geometry as summarized in the sequence model of Exxon group [2]. With the gas and oil exploration going deep in these years, sequence stratigraphy shows powerful vitality in some fields, such as member contrast, oil and gas bearing system, trap forecast, fine description of reservoir and hydrocarbon reservoir and so on. It will guide the gas and oil exploration. With the exploration of Ordos Basin, fruitful researches into sequence stratigraphy have been carried on about Upper Paleozoic in Ordos Basin [3-9], which are combined with the gas and oil exploration of Upper Paleozoic. But there still exists some problems in their researches: (1) the sequence stratigraphy model of epicontinental sea in Ordos Basin wasn’t established. (2) Benxi to Taiyuan formation formed in the epicontinental sea, which has subdued floor, mostly the sequence structures from Benxi to Taiyuan formation are duality system tract (it contains transgressive system tract and highstand system tract), and lowstand system tract was lacuna, or only existed on basin margin [3,7,9]. The studies we have performed showed that 8 sequence interfaces are recognized from Benxi to Taiyuan formation in Northeastern Ordos Basin. The sequence stratigraphy framework is established, and two models of sequence stratigraphy are established under the epicontinental sea background.

* Corresponding author. Tel.: +86-516-83591005; fax: +86-516-83590998.
E-mail address: yulinsh@sohu.com.

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1. Overview of study area

The study area is located in Northeastern Ordos Basin, lying in the ShanBei slope and through Western Shanxi flexural fold belt in present tectonic framework. The Neopaleozoic strata of Northeastern Ordos Basin contain Upper Carboniferous Benxi Formation and Jinci Formation, Lower Permian Taiyuan Formation and Shanxi Formation, Middle Permian Shihezi Formation and Upper Permian Shiqianfeng Formation (Fig. 1). The sedimentary system, sedimentary facies and its combination style are diversified, with the influence of tectonic descent, sea level change, and sediment supply. The research showed [7,8,10] that during the sedimentary period from Upper Carboniferous to Lower Permian it is carbonate flat-barrier bar-lagoon-shallow-water delta deposit, accompanied with meandering river deposit. River-dominated shallow-water delta is dominant in delta deposit, which forms coaly fixed sediment. During sedimentary period of the Middle to Upper Permian, with the uplift of north in Ordos Basin and regression of regional sea level, it is river-delta-lake system deposit, which forms terrigenous clastic rocks sedimentary formation.

2. Types and identification of sequence interface

The main sequence interfaces from Benxi to Taiyuan Formation are as follows.

2.1. Second order sequence interfaces

(1) The interface between Lower Paleozoic and Upper Paleozoic
   It is a regional unconformity interface, and it responds to the T10 reflection composite wave in seismic profile. The study area uplifts in Middle Ordovician, which is also called Caledonian event. The study area suffers 140 Ma weathering and denudation, and forms regional unconformity.

(2) The bottom surface of the main coal seam in Taiyuan formation
   It is a regional depositional break interface. It is the bottom surface of No.13 coal seam, and it responds to the T9-2 reflection composite wave in seismic profile. Its characteristics are as follows:
   • It is a regional tectonic regime interface. With the influence of third phase of Hercynian movement, it happens in late Upper Carboniferous. The tectonic framework changes from “uplift in south and inclination in north” to “uplift in north and inclination in south” [11].
   • It is a transgressive direction interface. Beneath the interface the seawater came from east and northeast that occurred in Upper Carboniferous, otherwise above the interface the seawater invaded from south and southeast in Lower Permian.
   • It is a surface of discontinuity in paleontological assemblage. Triticites zone are absent above the surface, which are abundant below the surface. The Sphaeroschwagerina-Pseudoschwagerina zone appear and are all-time prosperous.
   • It is also a sharp changing interface in trace element content. The trace element content analyses of No.13 coal seam floor shows that there are plenty of trace elements such as Zn, P, Sr, Ni, Li, Cu, and V, which reflect the deep water environment, and the value of Sr/Ba is also relatively low. So we can conclude that the sea level is at low position, and the trace element content in sedimentary aqueous medium is controlled by the influx of terrigenous clastic material. A fugacious exposure may exist before the formation of No.13 coal seam floor, which is eluviated by the fresh water.

(3) The bottom surface of “Beichagou sandstone” (K3 sandstone)
   It is interface of Taiyuan to Shanxi Formation, and it responds to the T9-1 reflection composite wave in seismic profile. Its characteristics are as follows:
   • It is a regional regression interface. Below the interface the transgression scale is up to the maximum extent and scale in Upper Paleozoic, which forms in sedimentary period of Taiyuan Formation. Above the interface the seawater withdraw to south, and the regional transgression event didn’t occur.
   • It is a river incision interface. The incision of K3 sandstone usually makes the top of Taiyuan Formation strata absent. For example the thickness of marine facies mudstone above the L5 limestone decreases and till dying out from south to north in study area.
Therefore Benxi to Taiyuan Formation is divided into 2 second-order sequences in Northeastern Ordos basin. They are quite to the 2 seismic sequences approximately, restricted by the 3 reflection composite waves (T_{10s}, T_{9.1}, T_{9.2}) in seismic profile.

2.2. Third order sequence interfaces

(1) The bottom surface of K₁ sandstone
It is a sedimentary system interface. Below the interface it was carbonate flat—barrier bar-lagoon deposit. Above the interface it is meandering river deposit in north of study area, and it is evolving to shallow—water delta-barrier bar-lagoon deposit in south. There is deepening to the underlying strata. It is typical in Liangjiaqi section in Hequ county Shanxi province. The K₁ sandstone erodes the L₅ limestone, which is located in upper of Benxi Formation (Fig. 2).

(2) The bottom surface of Qiaotou sandstone
It is also sedimentary system interface. Below the interface is tidal flat deposit. Above the interface is meandering river deposit in north of study area (e.g. Qiaotou section shown in Fig. 1). It changes to shallow-water delta deposit. It dies out in tidal flat deposit in south finally. There doesn’t exist Qiaotou sandstone deposit in the south of the line from Suide County to Liulin County. The river incision is obvious in north of study area, which incises the L₁ limestone or its corresponding strata (Fig. 3).

(3) The bottom surface of L₅, L₄, L₃ limestone
They are transgressive erosion surfaces. The sedimentary system changes above and below the surface. Below the surface is barrier bar-lagoon deposit, and above the surface is carbonate flat deposit. The three limestones all incise the underlying strata.

As mentioned above, Benxi to Taiyuan Formation is divided into 2 second-order sequences in Northeastern Ordos Basin, which are quite to the 2 seismic sequences. According to the erosion discontinuity surface, sedimentary system interface, stacking style of strata, paleosol and so on, they are subdivided into 7 third-order sequences, which contain 16 system tracts. The sequence stratigraphy framework is established in this area.

![Fig. 2. The sedimentary section map of K₁ sandstone in Northeastern Ordos Basin](image-url)
3. Characteristics of sequence stratigraphy

We only take the Qiaotou section as an example to introduce the characteristics of sequence stratigraphy in study area, located in north of this area.

3.1. Sequence 1

The bottom surface of this sequence is erosion surface of the Ordovician top (it is also a regional surface of unconformity), and its top surface is bottom surface of L_b limestone.

It contains transgressive system tract and highstand system tract. The transgressive system tract is composed of aluminous mudstone, and highstand system tract is composed of ferruginous mudstone.

3.2. Sequence 2

The bottom surface of this sequence is L_b limestone, and its top surface is bottom surface of K_1 sandstone.

It contains transgressive system tract and highstand system tract. The transgressive system tract is composed of L_b limestone mostly, or its facies change, marine mudstone deposit in local area. The L_b limestone represents the sedimentary filling of maximal transgression during the sedimentary period of Benxi Formation. The top surface of L_b limestone represents the maximum flooding surface. The highstand system tract is composed of ferruginous and aluminous mudstone, which is deposited in lagoon. It doesn’t preserve integrally because of the incision of K_1 sandstone in north borefield.

3.3. Sequence 3

The bottom surface of this sequence is K_1 sandstone, and its top surface is bottom surface of No.13 coal seam.
The sequence structure is three system tracts, including lowstand system tract, transgressive system tract and highstand system tract. It is river filling deposit, which is composed of pebbled coarse sandstone, coarse sandstone in lowstand system tract. It is flood plain mudstone with coal seam and mudflat mudstone deposit in transgressive system tract, with the influence of transgression, which forms the L₀ limestone. It is composed of pelitic siltstone and sandy mudstone in highstand system tract.

3.4. Sequence 4

The bottom surface of this sequence is bottom surface of No.13 coal seam, and its top surface is bottom surface of Qiaotou sandstone.

It contains transgressive system tract and highstand system tract. The transgressive system tract is made of No.13 coal seam, which is steady in study area. The strata don’t conserved integrally or even are lacuna in highstand system tract because of the river incision of Qiaotou sandstone. But it is composed of L₁ limestone and mudflat mudstone in south borefield of study area. The deposit forms in regression background.

3.5. Sequence 5

The bottom surface of this sequence is bottom surface of Qiaotou sandstone, and its top surface is bottom surface of L₄ limestone (or Lower Tumen shale, it is phase change of L₄ limestone, just as showing in Fig. 1).

It contains lowstand system tract, transgressive system tract and highstand system tract. Lowstand system tract is composed of river sandstone, which forms during the sedimentary period of river rejuvenation. Transgressive system tract is made of tidal flat mudstone, coal seam and carbonate flat limestone in the regional sea level ascending. The highstand system tract is composed of tidal flat silty mudstone and coal seam. The top surface of L₂₃ limestone represents the maximum flooding surface in this sequence.

3.6. Sequence 6

The bottom surface of this sequence is bottom surface of L₄ limestone, and its top surface is bottom surface of L₅ limestone (or Upper Tumen shale, it is phase change of L₅ limestone, just as showing in Fig. 1).

It contains transgressive system tract and highstand system tract. Transgressive system tract is composed of L₄ limestone or its phase change sediment, such as silty mudstone, shale. Highstand system tract is made of tidal flat silty mudstone and coal seam. L₄ limestone is widely regional distributed and purity in texture. It represents the production of max transgression in Upper Paleozoic in Ordos Basin.

3.7. Sequence 7

The bottom surface of this sequence is bottom surface of L₅ limestone, and its top surface is bottom surface of “Beichagou sandstone” (K₃ sandstone).

It contains transgressive system tract and highstand system tract. Transgressive system tract is composed of L₅ limestone or its phase change sediment (marine mudstone). But the distribution of L₅ limestone is relatively local compared with the transgression scale of L₄ limestone. The sediment is usually absent for the incision of “Beichagou sandstone” in highstand system tract.

4. Model of sequence stratigraphy

During the sedimentary period of Benxi and Jinci Formation (SQ1–SQ3), the carbonate rock overlapped from north to south, and the scale of transgression and difference of paleotectonic framework make the point of overlapping change regularly. With the influence of the paleotectonic framework and differential compacting action, river incision filling forms in lowstand system tract of study area in SQ3 during the sedimentary period of sea level descending. During the sedimentary period of Taiyuan Formation (SQ4–SQ7), the tectonic regime changed from “uplift in south and inclination in north” to “uplift in north and inclination in south” in Upper Carboniferous [11]. The main seam (No.13 coal seam) formed in residual sea during the tectonic alternative period. The top surface of
of coal seam represents the maximum flooding surface. With the regional tectonic framework going to steady gradually, the palaeogeomorphy with high in north and low in south going obviously, and the pricking up of altitude from north to south, the Qiaotou sandstone, which widely distributes from north to south, forms for the sea level descending to the lowest and the lowland forms by the differential compaction after the transgression, in lowstand system tract within sequence 5. The carbonate rock overlapped from south to north. The scale of transgression and the intensity of uplift in northern area make the point of overlapping change. Therefore, 2 types model of sequence stratigraphy are generalized from Benxi Formation to Taiyuan Formation.

4.1. Type model of ramp marginal basin in epicontinental sea background

The sequence structure of sequence 3 and sequence 5 contains lowstand system tract, transgressive system tract and highstand system tract. They form on the palaeoslope with high in north and low in south in the epicontinental sea background. There is subdued floor. There aren’t slope break and its relevant deposits such as basin floor fan, fan and slope fan in study area, even in Ordos Basin. With the sea level descending, which is relevant to the sea level descending after the L₀ limestone and L₁ limestone deposit, the river sediment incises the underlying strata consumingly, which can incise the barrier bar-lagoon deposit formed in low water onshore, and even the carbonate open subtidal sediment. But it will never continuously incise katadromically. The lowstand system tract is composed of low water wedge deposit with relatively thin thickness. The model of this type is similar to the type I model of ramp marginal basin (Fig. 4).

![Fig. 4. Distribution pattern of type I sequence stratigraphy in basin with ramp margin](image)

4.2. Type of ramp in epicontinental sea background

The other sequences are composed of transgressive system tract and highstand system tract, such as sequence 1, sequence 2, sequence 4, sequence 6, and sequence 7. They all form in epicontinental sea background. The transgressive system tract and highstand system tract in type II are similar to type I. Its characteristics are as follows: onlap of onshore exposure and shoreline break move down (move to the land); there isn’t incision on land with the relevance of river rejuvenescence and transference of sedimentary facies borderline towards basin. The model of this type is similar to the type II sequence model (Fig. 5).

![Fig. 5. Distribution pattern of type II sequence stratigraphy](image)
5. Conclusions

(1) Based on the study of the vertical sedimentary sequence, we have recognized the assemblage of vertical lithology, the geochemical test result of mudstone sample, and the characters of logs, the sequence stratigraphy interfaces such as regional unconformity, regional tectonic regime interface, sedimentary system interface, and transgression surface and so on.

(2) Benxi to Taiyuan Formation is divided into 7 third-order sedimentary sequences, and subdivided into 16 system tracts by the analysis of lithologic association, sedimentary facies and log response. Benxi to Taiyuan formation forms in the epicontinental sea, which has subdued floor, so most of the sequence structures from Benxi to Taiyuan formation are duality system tract. Tectonic disturbance, sea level change, and differential compaction provide enough accommodation space for distribution of K1 sandstone and Qiaotou sandstone. In this paper, we establish the framework and model of sequence stratigraphy from Benxi to Taiyuan formation in Northeastern Ordos Basin, which contains type I model of ramp marginal basin and type II of ramp in epicontinental sea background.

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