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Formation mechanism of favorable reservoirs in red beds in lower submember of fourth member of Shahejie Formation, Bonan Subsag, Jiyang Depression, Bohai Bay Basin

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Abstract: The red beds in the lower submember of the fourth member of Shahejie Formation (Es_4) in the Bonan Subsag of the Jiyang Depression of the Bohai Bay Basin have undergone a long period of sedimentation and diagenesis. The mechanism of primary pore retention and the evolution constraints of secondary pores are not clear, which restricts exploration. The controlling factors of favorable reservoirs in the red beds were analyzed by means of core observation, thin-section analysis of castings and scanning electron microscopy. Combined with analysis of reservoir characteristics, the formation mechanism of the favorable reservoirs was summarized, and their distribution was also predicted. There are two major sedimentary systems in the red bed sediments of the lower Es_4 submember of Bonan Subsag, including alluvial fan–braided river–braided river delta–lake and fan delta–lake. Sandstones are mainly lithic feldspars. Reservoir porosity is composed of residual primary pores, secondary dissolution pores and fractures. Physical properties of reservoirs are poor. The reservoir belongs to the category of ultra-low porosity and ultra-low permeability. Under the influence of mechanical compaction and the alternation of alkali and acid fluids, the reservoir porosity in the study area experienced three stages: primary pore retention, secondary pore formation and reservoir densification. Burial depth and favorable facies zones determine the preservation degree of primary pores, while organic acid, abnormally high pressure in overlying strata and fracture distribution determine the development of secondary pores. The favorable reservoirs with developed primary pores are fan-terminal reservoirs of alluvial fan buried less than 3 000 m, which are distributed as belts on the southern basin margin. The favorable reservoirs with developed secondary pores are braided river and braided river delta reservoirs with pressure coefficient greater than 1.2 in the upper submember of Es_4 and a developed fault system in the lower submember of Es_4, which are distributed in subsag zones in the pattern of strip-like and overlapping sheets.

Keywords: favorable reservoir; formation mechanism; red bed; lower Es_4 submember; Bonan Subsag; Jiyang Depression; Bohai Bay Basin

"Red beds" refer to the reddish-toned clastic deposits in the continental sedimentary environments [1–2]. As the early filling clastic rocks of the rift basin, the red bed shows a complicated distribution in favorable reservoirs [3–7]. A set of red bed sediments is widely distributed in the lower submember of the fourth member of Shahejie Formation (Es_4), Bonan Subsag, Jiyang Depression. Due to the large burial depth and high drilling costs, they have not attracted enough attention. With the improving exploration of the middle and shallow layers in recent years [8–9], it has become increasingly difficult in the discovery of high-quality reserves in the middle and shallow layers, and the red bed has gradually become the focus of exploration [10]. Recent exploration practices have suggested that the red beds of lower Es_4 submember in the Jiyang Depression are rich in oil and gas resources, especially the discovery of high-yield industrial oil flow in the L68 well area of the Bonan Subsag, which has promoted the exploration and development of red beds in the entire Jiyang Depression. However, in the follow-up drilling, it is difficult to obtain industrial oil flow in most of the exploration wells that encountered the red beds. One of the key factors behind failed wells is the unclear understanding of the development laws of favorable reservoirs. Due to the long-term sedimentation and diagenesis of red bed reservoirs, the primary pore retention mechanism and the secondary pore evolution are not clear, which leads to the lack of a systematic understanding of the distribution of favorable reservoirs in the red beds, hence hindering the exploration of red beds. In this paper, the red beds in the lower Es_4 submember of the Bonan Subsag are taken as the research object. On the basis of the characteristics of the reservoirs, the spatial evolution of red bed reservoirs is studied. Besides, the genetic types of

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favorable reservoirs are proposed and the distribution of favorable reservoirs is predicted. It is expected to provide guidance for oil and gas exploration in the red beds of this area.

1 Regional geological overview

The Bonan Subsag located in the northeast of the Jiyang Depression is the largest secondary subsag in the Zhanhua Sag, showing the characteristics of the fault in the north and overlap in the south, as well as faults in the east and west [8]. It is separated from the Chengdong Bulge by the Chengnan Fault in the north and connected to the Yihezhuang Bulge in the west through Yidong Fault; it is adjacent to the Shaojia Subsag and Sanhecun Subsag in the southwest and southeast respectively and transited to the Chenjiazhuang Bulge in the form of a gentle slope in the south, with an area of about 800 km^2 (Fig. 1). From bottom to top, the Bonan Subsag has mainly developed Paleozoic, Mesozoic and Cenozoic strata. The Cenozoic is developed completely and distributed widely, and it is the main strata of oil and gas exploration. It consists of the Paleogene Kongdian, Shaheji and Dongying Formations, the Neogene Guantao and Minghuazhen Formations, and the Quaternary Pingyuan Formation from bottom to top. The lower Es_4 submember, the study interval, belongs to the fourth member of Shahejie Formation (Es_4), which is a high-stand system tract with the second-order sequence (Fig. 2). It shows an unconformity contact with the upper Es_4 submember and generally belongs to the oxidation-to-semi-oxidation–half reducing sedimentary environments under arid climate conditions. Mudstones in the lower Es_4 submember are mainly red, affected by the nature of parent rock in the denudation area. From the subsag margin to the center, gray glutenite, middle-fine sandstone, siltstone with red sandy mudstone interbeds, and mudstone are developed successively. The single layer thickness of glutenite is generally in the range of 3–10 m, dominated by fine conglomerate, and sandstone is mainly distributed in the slope and subsag zones with a single layer thickness of 1–5 m [8].

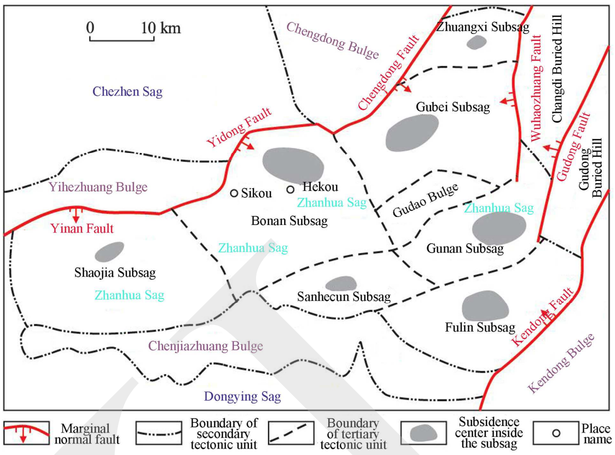

Fig. 1 Regional location of Bonan Subsag, Jiyang Depression, Bohai Bay Basin

2 Characteristics of red bed reservoirs

2.1 Sedimentary characteristics

During the sedimentary period of the lower Es_4 submember of Bonan Subsag, the Chenjiazhuang Bulge in the south, the Chengdong Bulge in the north and the Gudao Bulge in the east all provided the material sources for this subsag, and the materials from the Yihezhuang Bulge in the west are fewer [10–13]. The paleoclimate was arid and hot during the sedimentary period [14], and only a small lake basin was developed in the northern subsag zone, and all the rest areas were above-water and exposed. Impacted by the source area of the Chenjiazhuang Bulge in the south of the study area, it mainly

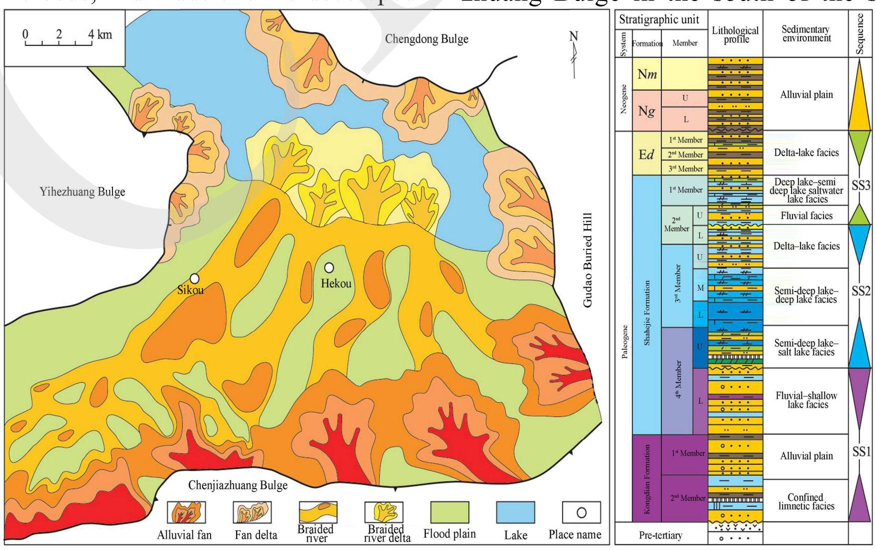

Fig. 2 Sedimentary facies and comprehensive column of lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

developed the sedimentary system of alluvial fan–braided river–braided river delta–lake. The east, west and north parts of the study area were controlled by the source areas of Gudao Bulge, Yihezhuang Bulge and Chengdong Bulge, respectively, which formed the fan delta–lake deposition system (Fig. 2).

2.2 Reservoir petrological characteristics

The results of core observation and thin-section analysis suggest that the reservoir lithology of the lower Es_4 submember of Bonan Subsag is mainly medium-fine sandstone, and glutenite is developed in the basin margin. The sandstone types are mainly lithic feldspar sandstone, followed by feldspar lithic sandstone and lithic sandstone. As the distance to the source area increases, the compositional maturities of sediments improve progressively after experiencing long-distance migration. The near-source alluvial fan and fan delta are dominated by lithic sandstone, with the volume fraction of quartz generally lower than 50%, feldspar lower than 20%, and debris generally higher than 50%. The braided river sediments far from the source are dominated by feldspar lithic sandstone and lithic feldspar sandstone, with the volume fractions of quartz and feldspar at 40%–60% and 20%–50%, respectively, and that of debris generally lower than 50%. The braided river delta that is the farthest from the source is dominated by lithic feldspar sandstone, and the volume fraction of quartz is 40%–60%, feldspar generally around 50%, and debris lower than 50% (Fig. 3). In general, the compositional maturities of different sedimentary facies in the lower Es_4 submember of Bonan Subsag vary significantly. The braided river delta has the best compositional maturity, followed by braided river deposition, and then alluvial fan and fan delta depositions.

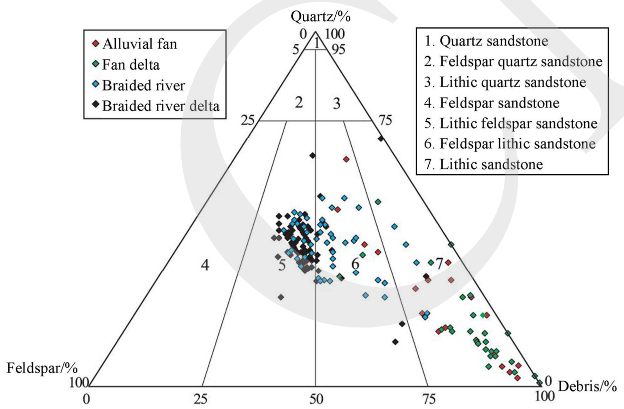

Fig. 3 Classification triangle map of sandstone reservoirs in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

2.3 Types and physical characteristics of reservoir spaces

The thin-section analysis of castings indicates that the reservoir spaces of the lower Es_4 submember of Bonan Subsag mainly consist of residual primary pores, secondary dissolution pores and a few fractures. The primary pores are mainly residual intergranular pores supported by rigid particles (Figs. 4a–b); there are also residual pores caused by the secondary edge enlargement of quartz (Figs. 4c–d) and the residual pores after the cementation of chlorite rings (Fig. 4e). The secondary pores are mainly intergranular and intragranular dissolution pores formed by carbonate cements dissolved by acidic fluids, feldspar and debris (Figs. 4f–i). In addition, there are also a small number of grain margin seams and fracture seams (Figs. 4f–j). The alluvial fan reservoir in this study area has the most developed primary pores, with the average porosity and permeability of 11.81% and 9.54 × 10^{-3} μm^2, respectively. The braided river reservoir mainly consists of the secondary pores, followed by partial primary pores, with the average porosity and permeability of 8.16% and 7.21 × 10^{-3} μm^2, respectively. The braided river delta reservoir is dominated by the secondary pores, with the average porosity and permeability of 7.94% and 2.26 × 10^{-3} μm^2, respectively. The fan delta reservoir is relatively tight as a whole, and a small number of secondary pores are observed, with the average porosity and permeability of 3.55% and 0.18 × 10^{-3}μm^2, respectively (Table 1). In general, the porosity of the lower Es_4 submember of Bonan Subsag is mainly 5%–10%. In addition, many sample points present the porosity of 10%–15% (Fig. 5a), with the permeability mainly between (0.1–5) × 10^{-3} μm^2, and some sample points have the permeability of higher than 5 × 10^{-3} μm^2(Fig. 5b). The reservoirs are relatively tight, with ultra-low porosity and ultra-low permeability, and some low-porosity and low-permeability reservoirs are also observed.

Table 1 Physical properties of different sedimentary facies in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

Sedimentary facies	Porosity/%			Permeability/10^{-3} μm^2		
	Min	Max	Average	Min	Max	Average
Alluvial fan	2.09	25.80	11.81	0.03	131.00	9.54
Braided river	0.05	18.73	8.16	0.05	169.26	7.21
Braided river delta	3.39	14.12	7.94	0.07	10.74	2.26
Fan delta	0.43	9.10	3.55	0.01	1.07	0.18

In summary, alluvial fan, braided river and braided river delta have good reservoir physical properties in this study area. The alluvial fan reservoir is located at the margin of the southern subsag, with shallow burial depth, and the reservoir space is mainly the primary pores. Braided river and braided river delta reservoirs are mainly located in the gentle slope and subsag zones, with medium to deep burial depth; the primary pore attenuates rapidly under the compaction, and the reservoir space is dominated by the secondary pores (Fig. 6). The fan delta that developed in the northern steep slope zone belongs to near-source sediments, with low compositional maturity and large burial depth; the reservoir space is dominated by the secondary pores, and the overall physical properties are poor (Fig. 6).

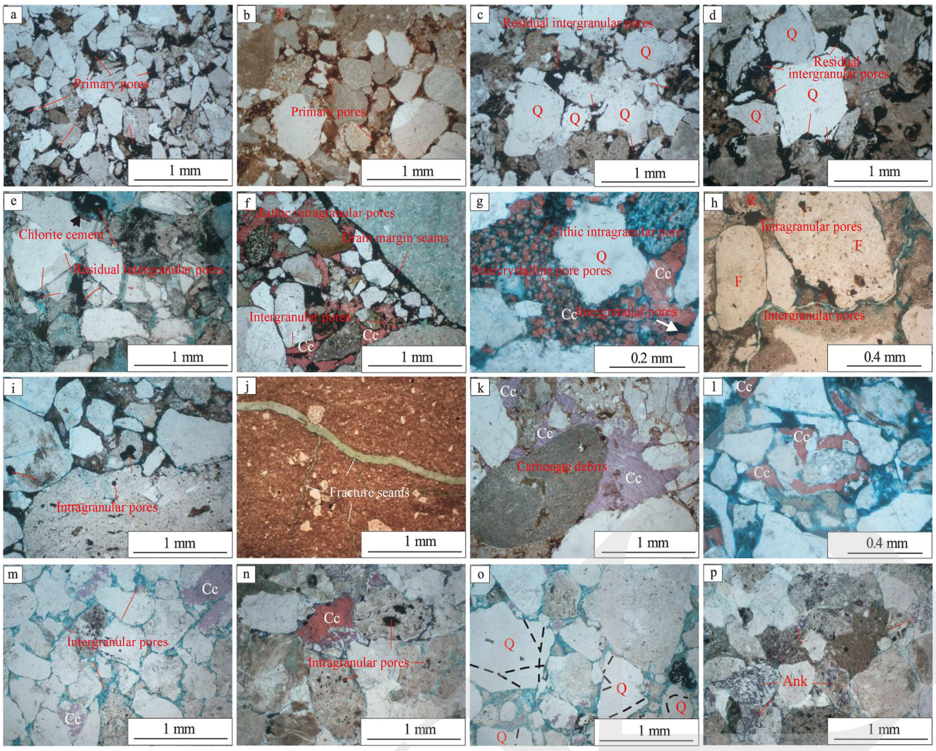

Fig. 4 Pore types and diagenesis of red beds in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

a. Primary pores are developed and filled with black organic matters; the sample is from Well Yi 193 at 2 941.41 m (observed under single polarized light). b. Residual primary pores are between the particles and filled with black organic matters; the sample is from Well Luo 10 at 2 438.21 m (observed under single polarized light). c. Secondary enlargement is observed in quartz (Q); the enlarged edge is filled with partial intergranular pores, and residual intergranular pores are filled with black organic matters; the sample is from well Yi 193 at 2 941.49 m (observed under single polarized light). d. Visible secondary enlargement is seen in quartz (Q), and residual intergranular pores are filled with black organic matters; the sample is from Well Yi 193 at 2 942.61 m (observed under single polarized light). e. Chlorite cement is found at the edge of particles; the cement occupies part of the pore space, with partial intergranular pores and filled with black organic matters; the sample is from Well Yi 160 at 3 080.65 m (observed under single polarized light). f. Intragranular pores are caused by debris dissolution and intergranular pore by the dissolution of red calcite cement (Cc), and seams appear at the grain margin; the sample is from Well Luo 358 at 2 779.61 m (observed under single polarized light). g. Intercrystalline pores are caused by the dissolution of red calcite cement (Cc) and intragranular pore by debris dissolution; the sample is from well Xinyishen 9 at 3 792 m (observed under single polarized light). h. Intergranular and intragranular pores are caused by feldspar (F) dissolution; the sample is from Well Luoxie 153 at 3 856 m (observed under single polarized light). i. Intergranular pores are caused by the dissolution of feldspar and debris; the sample is from Well Luoxie 153 at 3 853.8 m (observed under single polarized light). j. Fracture seams are developed; the sample is from Well Xinyishen 9 at 3 795.97 m (observed under single polarized light). k. Intergranular pores are filled with red calcite cement (Cc); the sample is from well Yi 130 at 2 333.76 m (observed under single polarized light). l. Intergranular and intragranular pores are filled with red calcite cement (Cc); the sample is from Well Xinboshen 1 at 3 753.87 m (observed under single polarized light). m. Mold pores are formed after feldspar dissolution and then filled with red calcite cement (Cc); partial residual intergranular pores (blue castings) are observed; the sample is from Well Luoxie 153 at 3 855.3 m (observed under single polarized light). n. Mold pores are formed after feldspar dissolution and then filled with red calcite cement (Cc)); intragranular pores are induced by debris dissolution and filled with black organic matters; the sample is from Well Yi 292 at 4 639.24 m (observed under single polarized light). o. Secondary enlargement is seen in quartz (Q), and more pores are occupied by the enlarged edge; the sample is from Well Luoxie 153 at 3 855.3 m (observed under single polarized light). p. Intragranular pores are formed by the dissolution of feldspar and debris and then filled with purple iron calcite cement (Ank); the particles are tight and present an concavo-convex contact; the sample is from Well Yi 292 at 4 639.24 m (observed under single polarized light).

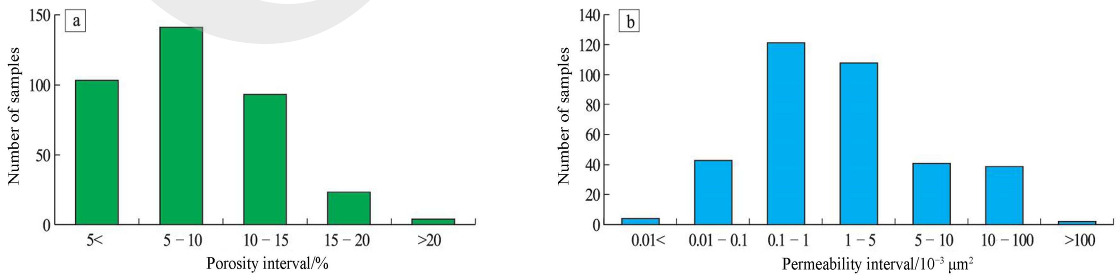

Fig. 5 Histogram of reservoir physical property distribution in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

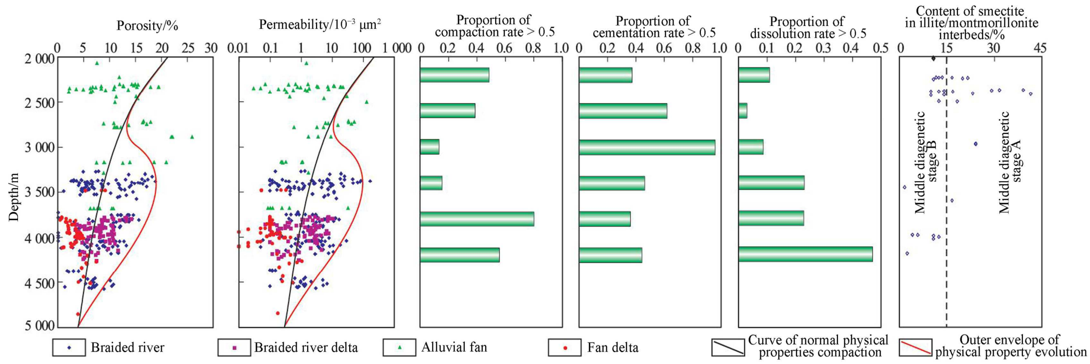

Fig. 6 Longitudinal distribution characteristics of reservoir physical properties and diagenetic parameters in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

3 Diagenesis and reservoir space evolution of red bed reservoirs

3.1 Diagenetic stage and diagenetic fluids

The red beds in the Bonan Subsag have generally experienced long-term diagenesis, with large burial depth and a long sedimentary period [15–19]. According to the content of smectite in the illite/montmorillonite interbeds of clay minerals, the study interval is mainly in the middle diagenetic stage B, or in the middle diagenetic stage A occasionally (Fig. 6).

The results of thin-section analysis and scanning electron microscopy suggest that the diagenesis, such as mechanical compaction, alkaline cementation and acidic dissolution, are mainly seen in the study area. Generally, compaction belongs to physical diagenesis, and its strength relates to the burial depth and the mineral's resistance to compaction, which is essentially determined by the composition and structure of rigid particles in rock minerals. Chemical diagenesis, such as alkaline cementation and acidic dissolution, mainly depends on nature and strength of diagenetic fluids. It is generally recognized that the red bed reservoirs were mainly modified by alkaline fluids in the early stage, affected by acidic fluids in the middle-late stage and by alkaline fluid environments in the later stage [3–4, 8]. The early alkaline fluids basically came from the alkaline synsedimentary water bodies derived from the arid sedimentary environments of red beds and the alkaline fluids discharged during the conversion of gypsum to anhydrite in the gypsum-salt rock system of the upper Es_4 submember, and the alkaline fluid is the root cause of carbonate cement. The acidic fluids in the middle stage are believed to be mainly derived from the organic acids associated with the hydrocarbon generation and expulsion in the source rocks. However, there is no effective source rocks observed in the lower Es_4 submember and the underlying Kongdian Formation of Bonan Subsag. The results of oil-source correlation suggest that the discovered oil and gas in the red beds of the lower Es_4 submember are all derived from the source rocks in the upper Es_4 submember. This indicates the smooth fluid exchange between the upper and lower Es_4 submembers. Therefore, the organic acids for the acid dissolution of red beds in the lower Es_4 submember should mainly come from the source rocks in the upper Es_4 submember. The alkaline fluids environment in the late stage resulted from the gradual decomposition of organic acids caused by the increased burial depth and ground temperature [3–4, 8]. Under the action of alkaline fluids generated during the conversion of clay minerals, the formation water was shifted into weak-alkaline formation fluids progressively.

3.2 Reservoir space evolution of red beds

3.2.1 Early stage of alkaline fluids cementation

After sedimentation, the red beds in the lower Es_4 submember are first affected by alkaline fluids. This stage is characterized by mechanical compaction and alkaline cementation, and compaction and cementation-induced porosity reduction dominate the evolution of reservoir spaces. At the burial depth of 2 000 m, the proportion of samples with a compaction ratio greater than 0.5 is close to 50% (Fig. 6), indicating strong compaction. Meanwhile, impacted by the alkaline synsedimentary water bodies, the proportion of samples with a compaction ratio greater than 0.5 is close to 40%. Along with the increase in burial depth, a large number of alkaline fluids generated by the dehydration of gypsum-salt rock in the upper Es_4 submember reached this interval, leading to stronger alkaline cementation (Figs. 4f, k, l). The proportion of samples with a cementation ratio greater than 0.5 increases over time at a buried depth of 2 000–3 000 m (Fig. 6), and the primary pores filled with a large amount of cement suppress the compaction to a certain extent. Therefore, the proportion of samples with a compaction ratio greater than 0.5 tends to decline gradually (Fig. 6).

In general, this stage witnesses the declining reservoir space, which is dominated by alkaline fluids and mainly presents porosity reduction induced by compaction and cementation. All types of reservoirs in the study area have been affected by alkaline fluids. After this stage, the mineral particles in the red bed reservoirs are in point-to-line contact (Fig. 7), and the reservoir space is still dominated by primary

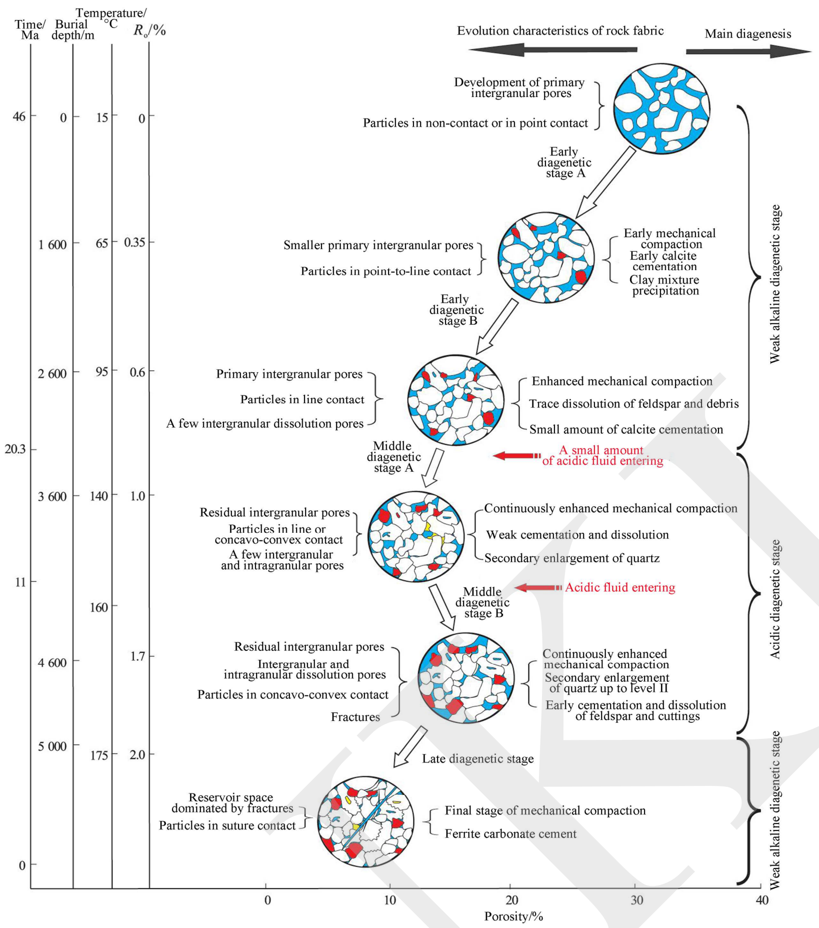

Fig. 7 Diagenetic pattern and pore evolution of red beds in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

intergranular pores. The red bed reservoirs in this stage are mainly concentrated in the subsag margin zone with a burial depth smaller than 3 000 m, and the corresponding sedimentary facies is alluvial fan (Figs. 2 and 6).

3.2.2 Middle stage of acidic fluid dissolution

As the burial depth of the red bed reservoirs increased, the source rocks in the overlying upper Es_4 submember gradually reached the hydrocarbon generation threshold and began to generate and expel hydrocarbons. Driven by abnormally high pressure, the organic acids generated during the hydrocarbon generation of source rocks laterally docked with the lower Es_4 submember and entered the red bed reservoirs through the faults. They convert the diagenetic environment of red bed reservoirs from weakly alkaline to weakly acidic, resulting in acidic dissolution [9]. As the burial depth further increased, the source rocks in the overlying upper Es_4 submember began to generate and expel hydrocarbons in a large scale, and the produced organic acids entered the red bed reservoirs in the lower Es_4 submember massively, leading to the acidic diagenetic environment [18]. In this study area, evident acid dissolution of red bed reservoirs can be observed at a burial depth more than 3 000 m, and acid dissolution gradually increases with burial depth. Within the burial depth range from 3 000 to 4 500 m, the proportion of samples with a dissolution ratio greater than 0.5 increases and the cementation rate decreases simultaneously (Fig. 6). Acid dissolution of feldspar and debris is visible, and secondary dissolution pores are developed in a large scale, forming the secondary pore zones. The development of secondary pores provides the space for mechanical compaction, and the compaction rate tends to grow (Fig. 6).

In general, this stage retains the reservoir space, which is dominated by acidic fluids and mainly undergoes the pore increment by dissolution and pore reduction by compaction. After this period, the primary pores in the red bed reservoirs are reduced, and the intergranular and intragranular dissolution pores are increased (Figs. 4m, n). The secondary enlargement of quartz is obvious (Fig. 4o), and the particles are in line or concavo-convex contact (Fig. 7). The red bed reservoirs undergoing this stage are mainly concentrated in the southern slope zone, northern subsag zone and steep slope zone with a burial depth of 3 000–4 500 m, and the corresponding sedimentary facies are the braided river, braided river delta and fan delta, respectively. However, the compositional and structural maturities of fan delta reservoirs are poor. After the early influence of alkaline fluids, the primary pores are rarely left due to pore reduction induced by cementation and compaction, while the reservoir is absent of organic acid-communicating channel itself. Meanwhile, the fan delta is mostly located at the edge of subsag and is relatively far from the hydrocarbon generation center of the upper Es_4 submember. The reservoir itself is little impacted by organic acids; although the fan delta is modified by acidic fluids, the induced secondary pores are small in number, so the reservoir is tight. Therefore, the middle-stage acidic fluid mainly dissolves reservoirs of braided rivers and braided river delta, forming the secondary pore zones (Fig. 6).

3.2.3 Late stage of alkaline fluid cementation

As the burial depth increases and the ground temperature rises up, the organic acids are gradually decomposed and the acidic fluids are depleted, converting the formation water to a weakly alkaline state. At this stage, the rock continuously reaches the compaction limit. The compaction-induced porosity reduction dominates the evolution of reservoir space. Meanwhile, under the influence of a weak alkaline fluid environment in the late period, the iron calcite cement emerges and fills the reservoir space (Fig. 4p), and the reservoir space is compacted and cemented over time. In general, the red bed reservoirs are very tight at this stage, and partial fracture seams of mineral particles are developed under strong compaction. The rocks have been basically compacted to the most extent [20–21] with particles in sutured contact, and a small amount of iron carbonate cement is found (Fig. 7).

4 Prediction on the distribution of favorable red bed reservoirs

Studies on the diagenetic evolution laws of red bed reservoirs suggest that there are two types of favorable reservoirs developed in the study area, which are the alluvial fan reservoirs with primary pores (burial depth less than 3 000 m), and reservoirs of braided rivers and braided river delta with secondary pores (burial depth above 3 000 m).

4.1 Distribution of favorable reservoirs with primary pores

Alluvial fan reservoirs with primary pores are different in the particle composition and structural maturity among subfacies, which determines the difference in resistance to compaction and the retention of primary pores. In general, the root-fan subfacies has the worst sediment composition and structural maturity, as well as the lowest resistance to compaction. After experiencing a long-distance migration, the fan-end subfacies has the relatively good sediment composition and structural maturity, and strong resistance to compaction. The mid-fan subfacies is between those of the root-fan and the fan-end, and the resistance to compaction of subfacies sediments are different, which ultimately results in different physical properties of subfacies reservoirs. The average porosities of alluvial root-fan, mid-fan and fan-end of the lower Es_4 submember of Bonan Subsag are 9.35%, 12.71% and 17.01%, respectively. Therefore, the favorable subfacies type with a high retention rate of primary pores in the alluvial fan reservoirs is mainly at the fan-end. The favorable reservoirs with primary pores are mainly located in the southern basin margin in a belt-shaped distribution, namely the front of alluvial fan charged by the material source in the Chenjiazhuang Bulge (Fig. 8).

4.2 Distribution of favorable reservoirs with secondary pores

The secondary pores in the reservoirs of braided river and braided river delta in the study area is benefited from the dissolution of organic acids generated by source rocks in the overlying upper Es_4 submember. Driven by the abnormally high pressure in the central subsag, the organic acids in the

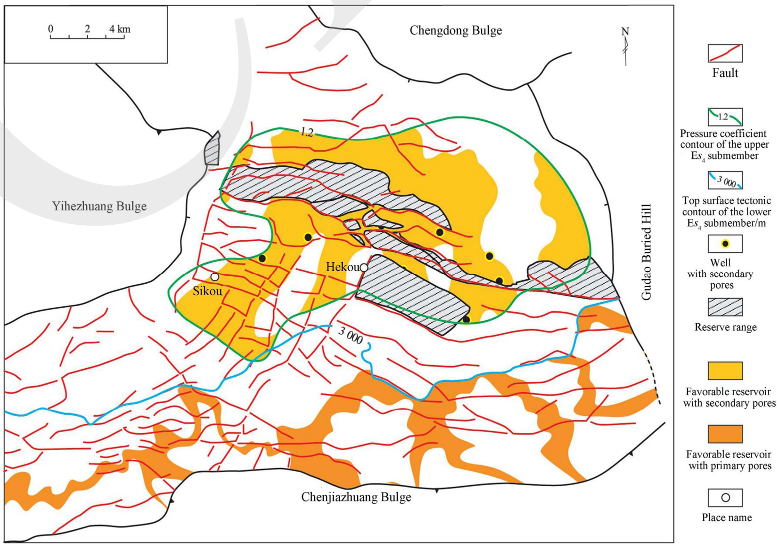

Fig. 8 Distribution of favorable reservoirs in lower Es_4 submember in Bonan Subsag, Jiyang Depression, Bohai Bay Basin

upper Es_4 submember enter the red bed reservoirs through fault conduction or directly docking the lower Es_4 submember. The source rocks of the upper Es_4 submember are concentrated in the central subsag. Therefore, the wells are also densely deployed in the central subsag where the lower Es_4 submember is strongly eroded by organic acids and develops the secondary pores (Fig. 8). The reservoirs of braided rivers and braided river delta are located in this area (Fig. 2); the alluvial fan and fan delta at the margin of the subsag are far away from the source rock area in the upper Es_4 submember and the abnormally high pressure center of the overlying strata. Due to lack of fault conduction, they are also not affected by organic acids and are in a normal compaction zone [22–26]. Therefore, the strong influence of organic acids in the central subsag, the abnormally high pressure of overlying strata and the faults communicating with organic acids are the key factors that determine the development of secondary pores in the red bed reservoirs.

The favorable reservoirs with secondary pores in the study area are mainly found in the braided-river and braided-river-delta reservoirs of the subsag zone in the pattern of belt and overlapping sheet (Fig. 8) by comprehensively considering the distribution of subsag zones, the 1.2 pressure coefficient contour of the upper Es_4 submember, as well as the distributions of faults, braided-river and braided-river-delta reservoirs in the lower Es_4 submember. In fact, the exploration wells with secondary pores and the discovered oil and gas reserves in the lower Es_4 submember also mainly concentrate in this area (Fig. 8).

5 Conclusions

(1) There are two types of sedimentary systems in red beds of the lower Es_4 submember of the Bonan Subsag, namely alluvial fan–braided river–braided river delta–lake and fan delta–lake. The alluvial fan and fan delta sediments are dominated by lithic sandstone; the braided river sediments are dominated by feldspar lithic sandstone and lithic feldspar sandstone; the braided river delta is controlled by lithic feldspar sandstones. The alluvial fan reservoir is mainly with primary pores of good physical properties. The braided-river and braided-river-delta reservoirs are controlled by the secondary pores with medium physical properties; the fan delta reservoirs are tight and their physical properties are poor.

(2) The red bed reservoirs in the lower Es_4 submember of the Bonan Subsag are mainly found in the middle diagenetic stage B and occasionally in the middle diagenetic stage A. The red bed reservoirs underwent three diagenetic evolution processes, namely the early alkaline cementation, the middle acid dissolution, and the late alkaline cementation. Primary pores remained after the early alkaline cementation; a large number of secondary pores were formed after acidic erosion in the middle stage; affected by the late alkaline cementation, the space of some reservoirs was depleted and those reservoirs were tight.

(3) The favorable reservoir with primary pores is mainly determined by the burial depth and favorable facies zones. This type of favorable reservoirs in the study area is developed in the southern subsag margin (burial depth below 3 000 m), and it is located at the front of alluvial fan in belt-shaped distribution. The favorable reservoir with secondary pores is mainly controlled by organic acids, the abnormally high pressure of overlying strata and fault systems. This favorable reservoir in the study area is located in the development zone of braided-river and braided-river-delta reservoirs, distributing in the pattern of belt and overlapping sheet.

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