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Analysis of Diagenetic Evolution and Pore Structure Response Mechanism of Low Permeability Sandstone Reservoir in Chang 6 Member of Yanchang Formation

Kaixuan Liu[1], Jiangtao Wang[2]

[1]1School of Earth Sciences and Engineering, Xi'an Shiyou University, Xian 710300 China
[2]Yanchang Oil Mine Management Bureau Xingzichuan Drilling Company, Yanan 716000, China

ABSTRACT

The low permeability sandstone reservoir in Chang 6 member of Yanchang Formation in Ordos Basin is one of the important oil-bearing strata in China, but its low permeability characteristics pose a great challenge to oil and gas exploitation. In this paper, the diagenetic evolution process and pore structure characteristics of low permeability sandstone reservoirs in Chang 6 member of Yanchang Formation are systematically analyzed, and the response mechanism between diagenesis and pore structure is discussed. The research results show that the sandstone reservoir in Chang 6 member has experienced complex diagenesis, including mechanical compaction, cementation and dissolution, which are intertwined and have a profound impact on the pore structure of the reservoir. Compaction makes particles closely arranged and reduces porosity; Cementation further blocks pores and throats, significantly reducing permeability; However, dissolution forms secondary pores by dissolving some minerals, which improves reservoir physical properties to some extent. In the process of diagenetic evolution, the pore types gradually changed from primary macropores to micropores and nanopores, and the pore throat structure showed the evolution characteristics of "fine granularity", which led to the decrease of reservoir permeability. In addition, dissolution has a double effect of "compensation-limitation". Although it can generate secondary pores to improve permeability, dissolution products often re-precipitate in the form of authigenic minerals, which inhibits the further expansion of pores. The study shows that the balance of "destruction-filling" dominated by compaction-cementation and the double effect of dissolution are the key factors leading to the low permeability characteristics of reservoirs.

KEYWORDS

Yanchang Formation; Diagenetic evolution; Pore structure; Response mechanism; Low permeability; Sandstone reservoir; Ordos basin; Chang 6 member.

1. INTRODUCTION

As an important energy base in China, the Ordos Basin has abundant reserves of oil and natural gas resources, which play a crucial role in ensuring national energy security. Among them, the Yanchang Formation is an important oil and gas bearing formation in the basin, and the Chang 6 Member, as one of the core production layers of the Yanchang Formation, has a wide distribution range and enormous exploration and development potential [1-2]. However, the long 6-section sandstone reservoir generally exhibits low-permeability characteristics, poor reservoir properties, porosity mostly concentrated between 8% and 12%, and permeability generally lower than $0.1 \times 10^{-3}\ \mu m^2$, which greatly increases the difficulty of oil and gas extraction and restricts the efficient development of oil and gas fields.

The low permeability of reservoir is closely related to its diagenetic evolution process. During the long geological history, the sandstone of Chang 6 member experienced complex diagenesis, including compaction, cementation and dissolution. These diagenesis are intertwined, which has a profound impact on the pore structure of the reservoir [3]. For example, compaction will lead to tight arrangement of rock particles and compression of pore space; Cementation will further block pores and throats and reduce permeability; However, dissolution may dissolve some minerals, form secondary pores and improve reservoir physical properties [4]. Therefore, it is of great theoretical and practical significance to study the diagenetic evolution process of low permeability sandstone reservoir in Chang 6 member of Yanchang Formation and reveal the response mechanism between it and pore structure for accurately evaluating reservoir quality, predicting oil and gas enrichment law and formulating reasonable development plan.

2. REGIONAL GEOLOGICAL BACKGROUND

The tectonic evolution of Ordos basin has a long history, which mainly experienced two important tectonic stages: Indosinian Movement and Yanshan Movement. Throughout the Triassic era, the Indosinian orogeny triggered the subsidence of the basin's basement, thereby creating accommodation space for ensuing sedimentary deposition. Later, in the Cretaceous period, the Yanshanian orogeny resulted in uplift of the eastern portion of the basin, whereas the western segment experienced relative subsidence. This ultimately gave rise to an asymmetric syncline structure characterized by a higher eastern flank and a lower western flank. This tectonic configuration has had a profound influence on sedimentation and diagenesis within the basin. Particularly during the sedimentation phase of the Chang 6 member, the basin was in a phase of lacustrine basin expansion, with a well-developed deep-water sedimentary slope break zone. This setting provided the basis for the formation of low-permeability sandstone reservoirs.

The Ordos Basin ranks among China’s largest cratonic sedimentary basins, with the Upper Triassic Yanchang Formation (comprising members Chang 1-10) serving as its most significant hydrocarbon-bearing unit. Within this formation, the Chang 6 member (Chang 6) stands out as the primary target for exploration and development. This interval is characterized by tight sandstone reservoirs exhibiting low porosity (typically 5%-15%), minimal permeability (generally <1 mD), and strong capillary resistance [5-6]. Sedimentologically, the depositional setting was largely influenced by sub-environments of braided river delta fronts, resulting in sand bodies that are predominantly thick, layered blocks or medium-thick strata. These sands display low compositional maturity, with quartz accounting for 50%-70%, feldspar at 15%-30%, and rock fragments making up 10%-20%. The cements present are chiefly calcite, clay minerals (such as illite and chlorite), and zeolite (Table 1).

Table 1 Basic characteristics of low porosity and permeability in Chang 6 reservoir

Rock type	Quartz (%)	Feldspar (%)	Rock debris (%)	Cement (%)	Porosity (%)	Permeability (mD)
Fine sandstone of Chang 6 member	62-68	20-25	8-12	Calcite 10-15	8-12	0.3-0.8
Siltstone of Chang 6 member	55-60	15-20	15-20	Clay 15-20	5-8	0.1-0.3

The sedimentary system of Chang 6 member in Ordos Basin is diverse and complex. The main types of sedimentary facies include subaqueous distributary channel, estuary bar, lake shoal and sandy debris flow sediment [7]. These different sedimentary facies types together constitute the sedimentary system of this period.

In terms of sand body distribution, different regions show certain differences. Huaqing area is dominated by thick-layer massive sand bodies with sandy clastic flows, which usually have good connectivity and high porosity [8]. In Huangling area, however, the delta front slump turbidite fan is mainly developed, which usually has strong sorting and high compactness. These differentiated sand body distribution characteristics have an important impact on the pore structure and permeability of reservoirs, and also provide an important geological background for the subsequent study of diagenetic evolution and pore structure response mechanism.

3. DIAGENETIC EVOLUTION SEQUENCE AND STAGE DIVISION

3.1. Diagenesis type

Diagenesis mainly includes mechanical compaction, cementation, metasomatism, filling, dissolution, dissolution and authigenic mineral precipitation, which have an important impact on reservoir properties during the burial and evolution of sedimentary rocks. Mechanical compaction makes particles closely arranged and reduces porosity [9].

Cementation is the core factor of reservoir densification in Chang 6 member, with calcite cementation accounting for 70%-80% of the total cementation and clay cementation illite and chlorite as the main factors (Table 2). Calcite cementation is mostly filled along the grain edge or pore, forming "continuous crystal" or "pore" cementation; Clay cementation exists in the form of pore lining or pore filling, which significantly reduces pore connectivity [10-11]. There is a significant negative correlation between the cement content and porosity. When the cement content is more than 15%, the permeability is mostly less than ＜0.5 mD

Table 2 Agglutination

Cementite type	Average content (%)	Main occurrence	Influence on porosity
Calcite	8-12	Pore filling, particle edge	Directly plug the pore throat and reduce porosity
Clay mineral	5-8	Pore lining and filling in the hole	Reduce the throat radius and connectivity
Laumontite	2-5	Secondary pore filling	Partial improvement of pore type

Cementation makes the rock compact by filling pores with cements such as Shi Ying and calcite. Metasomatism changes mineral composition and structure; The filling action includes the filling of pores by heterobase and authigenic minerals, which reduces the permeability; Dissolution can form secondary pores and improve pore structure to some extent; While dissolution and authigenic mineral precipitation jointly affect the evolution process of pores [12]. Generally speaking, these diagenesis may not only worsen reservoir physical properties, but also improve reservoir performance locally, but their effects are usually uneven and limited.

3.2. Diagenetic stage division

The low-permeability sandstone reservoirs in the sixth section of the Yanchang Formation are usually in the late diagenetic stage A, during which diagenesis is strong. The main characteristics include high organic matter maturity, vitrinite reflectance exceeding 1.3%, and entering the peak period of hydrocarbon generation [13]. The generated hydrocarbon fluids have a significant impact on the diagenetic process; The overall density of the rock is dense, with particles mainly in linear contact to concave convex contact, and some visible pressure solution phenomena, reflecting strong compaction and pressure solution effects, resulting in low porosity and permeability; Self-generated minerals, including quartz, calcite, dolomite, and various clay minerals, are extensively present. Their formation is intricately linked to the diagenetic environment and the characteristics of the fluids involved, which in turn alter the pore architecture of the reservoir. While compaction and cementation processes notably diminish the primary pores, minerals like feldspar and rock fragments undergo dissolution due to the influence of acidic fluids. This results in the creation of a significant number of secondary pores, such as intragranular and intergranular dissolution pores, which offer crucial space for the storage and migration of hydrocarbons.

4. CHARACTERISTICS AND CLASSIFICATION OF PORE STRUCTURE

4.1. Pore structure characteristics

The pore structure of low permeability sandstone reservoir in Chang 6 member of Yanchang Formation is mainly secondary pores, which are strongly reformed by diagenesis and show complex pore types and distribution characteristics. Primary pores are mainly residual intergranular pores, with large pore size but poor connectivity, which are often separated by chlorite coating or intergranular pores; The secondary pores formed by dissolution are the main reservoir spaces, including irregular pores (0.2-26 μm) produced by feldspar dissolution, and turbidite dissolution pores (1-100 μm) widely distributed in distributary channel sand bodies. The latter has good connectivity and dendritic throat structure and is an important part of high-quality reservoirs [14]. In addition, structural cracks (such as pressure-dissolving cracks and tectonic fracture) are developed, although the width is small (micron level), but the permeability can be partially improved; Heterogeneous pores such as shrinkage pores and intergranular pores are extremely small (0.1-2 μm) and have poor connectivity, so they need to rely on fracture system to effectively participate in the reservoir [15]. On the whole, the pore structure of the reservoir is complex and heterogeneous, and it needs the synergy of various pores to form an effective reservoir.

4.2. Pore structure classification

According to pore types, diagenesis and physical parameters, the pore structure of reservoirs can be divided into the following four categories (Table 3). According to pore types, it can be divided into residual primary intergranular pore dominant type (permeability 0.01–0.1) and dissolution pore dominant type (0.1–1.0). The former has poor connectivity, which is affected by strong compaction and chlorite cementation, while the latter has tree-like throat with good connectivity, which is related to weak dissolution and turbidite cementation. According to the throat morphology, it can be divided into mesopore-fine throat type (permeability < 0.1), pore throat is poorly sorted and controlled by carbonate cementation, and micropore-dense mesh throat type (0.1–1.0), which has medium connectivity and is affected by the superposition of dissolution and cementation. According to the physical properties, the porosity of Class I high-yield reservoir (permeability > 0.1) is more than 3%, with high oil saturation, often accompanied by dissolution and fracture development, while the porosity of Class IV low-yield reservoir (permeability < 0.01) is less than 1%, dominated by strong compaction and cementation, and the overall performance is characterized by low porosity and low permeability [16].

Table 3 Pore structure of four types of reservoirs

Classification basis	Type	Feature description	**Range of permeability (10^{-3} μ m ^{2})**	Typical diagenetic influence
Pore dominant type	Residual primary intergranular pore dominant type	The proportion of residual intergranular pores is high, and the throat is mainly curved, with isolated pores and poor connectivity.	0.01-0.1	Strong compaction and chlorite cementation
	Dissolution hole dominant type	Dissolved pores (feldspar and turbidite) are dominant, and the throat is tree-like with good connectivity.	0.1-1.0	Weak dissolution, turbidite cementation
Laryngeal morphology	Mesoporous-thin throat type	Pores are mainly mesopores (50-200 μm), with small throat radius (< 10 μm) and poor sorting.	<0.1	Strong compaction and carbonate cementation
	Micropore-dense mesh throat type	Micropores (< 50 μm) coexist with dense reticular throat, and the connectivity is moderate.	0.1-1.0	Dissolution-cementation superposition
Physical parameters	Class I reservoir (high yield)	Porosity>3%, permeability>0.1 × 10^{-3} μ m ^{2}, oil saturation>60%	>0.1	The dissolution is remarkable and the cracks are developed
	IV reservoir (low production)	Porosity<1%, permeability<0.1 × 10^{-3} μ m ^{2}, oil saturation<35%	<0.01	Strong compaction and cementation are dominant

5. RESPONSE MECHANISM OF DIAGENETIC EVOLUTION AND PORE STRUCTURE

The diagenetic progression of the Chang 6 reservoir can be categorized into three distinct phases: the early diagenetic phase (with burial depths ranging from 0 to 2,000 meters), the middle diagenetic phase (from 2,000 to 3,500 meters), and the late diagenetic phase (exceeding 3,500 meters). Each of these phases exhibits notable variations in the dominant diagenetic processes and pore structure attributes (see Table 4).

During the early diagenetic phase, mechanical compaction is the primary diagenetic process. Primary intergranular pores are abundant, resulting in high porosity and favorable permeability. In contrast, the middle diagenetic phase is marked by intensified cementation and dissolution. The number of residual primary pores decreases, while dissolution pores and turbidite intergranular pores increase, leading to a decline in overall physical properties. In the late diagenetic stage, calcite cementation made pores mainly micropores and fractures, with low porosity and poor permeability, showing a strong densification trend as a whole.

Table 4 Diagenesis and pore structure characteristics

Diagenetic stage	Dominant diagenesis	Pore type	Porosity (%)	Permeability (mD)	Key control factors
Early diagenetic stage A	Mainly mechanical compaction	Primary intergranular pores (> 5 μ m)	25-30	1-3	The deposition rate is fast and the particle sorting is poor
Early diagenetic stage B	Mechanical+early chemical compaction	Primary intergranular pores (2-5 μm)	15-20	0.5-1	Directional arrangement of clay minerals
Middle diagenetic stage A	Calcite cementation+ weak dissolution	Residual primary pores+a few dissolved pores	10-15	0.3-0.5	With the increase of buried depth, the ground temperature rises (80-120℃)
Middle diagenetic stage B	Strong dissolution+turbidite cementation	Dissolved pores+intergranular pores (turbidite)	8-12	0.2-0.4	When the ground temperature reaches 120-150℃, organic acids are enriched
Late diagenetic stage A	Late calcite cementation	Micropores (< 2 nm)+cracks	5-8	＜0.2	Buried depth＞ ＞4000 m, pressure closed

One of the core logics of the response mechanism is the "failure-filling" balance dominated by compaction and cementation. In the early stage of diagenesis, mechanical compaction rapidly compressed the primary pores between particles, significantly reducing the reservoir porosity; Subsequently, cementation further fills the remaining pore space through the precipitation of minerals such as Shi Ying and calcite, which makes the rock tend to be dense. Statistics show that the porosity of reservoir is negatively correlated with the cement content and buried depth, indicating that the synergistic effect of compaction and cementation is the key to lead to low permeability characteristics.

Secondly, dissolution has a double effect of "compensation-limitation". On the one hand, the dissolution of unstable minerals such as feldspar and turbidite by acidic fluid can generate secondary pores, which can improve reservoir permeability to some extent; On the other hand, dissolution products, such as clay minerals, often re-precipitate in pores in the form of authigenic minerals, but become new cements, which inhibit the further expansion of pores. Therefore, although dissolution is widespread, the proportion of secondary pores formed by it is usually low (generally less than 10%), so it is difficult to fundamentally change the reservoir densification trend.

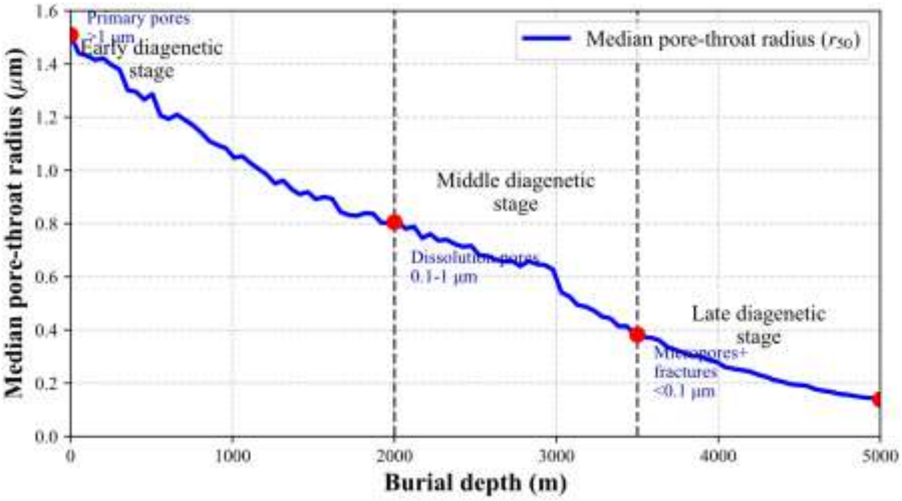

Figure 1 Evolution characteristics of pore throat structure during diagenetic evolution

In addition, the pore throat structure exhibits a "fine-grained" evolution characteristic. With the advancement of diagenesis, the pore types evolve from primary macropores (>5 μm) in the early diagenetic stage to micropores (<2 nm) and nanopores (2-50 nm). Concurrently, the median pore throat radius (r_{50}) reduces from an initial value of >1 μm to <0.1 μm by the late diagenetic stage (see Figure 1). This progressive refinement of the pore system results in a significant decline in reservoir permeability and the development of a high capillary resistance environment, thereby amplifying the low-permeability nature of the reservoir.

6. CONCLUSION

The low permeability sandstone reservoir in Chang 6 member of Yanchang Formation in Ordos Basin has experienced a complex diagenetic process, mainly including mechanical compaction, cementation and dissolution, which have jointly affected the reservoir physical properties. The reservoir is mainly in the late diagenetic stage A, characterized by high maturity of organic matter and significant influence of hydrocarbon fluid on diagenetic process, resulting in low porosity and permeability; Although some secondary pores (such as intragranular and intergranular dissolved pores) were formed by acid fluid dissolution, the overall improvement was limited. The pore structure is mainly secondary pores, including residual intergranular pores with poor connectivity, irregular pores formed by feldspar dissolution, and turbidite dissolution pores with good connectivity and dendritic throat structure, accompanied by structural fractures to improve permeability locally. The "destruction-filling" balance dominated by compaction-cementation is the key to reservoir densification. Although dissolution is helpful to improve permeability, its contribution is limited, and it is difficult to fundamentally change the density characteristics of reservoirs. Understanding these diagenetic evolution and pore structure response mechanisms is very important for accurately evaluating reservoir quality, predicting oil and gas enrichment law and making development plans.

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