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Pore Structure and Physical Properties of Sandstone Reservoirs: A Case Study of Chang 6 Member in Antaolin Area, Ordos Basin

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Abstract

This study takes the Chang 6 sandstone reservoir in the Antaolin area as the research object. Through comprehensive experimental methods including casting thin sections, scanning electron microscopy (SEM), and mercury intrusion porosimetry (MIP), we systematically analyzed the microscopic pore-throat structure characteristics of the reservoir. The main understandings are as follows:In terms of petrological characteristics, the study area mainly develops two types of reservoir rocks: feldspathic sandstone and lithic arkose. The cements contain relatively abundant carbonate minerals and clay minerals, with minor amounts of siliceous and feldspar cements. The clay minerals are mainly composed of chlorite and illite. The rock pore structure is complex, with poor throat sorting uniformity.Pore structure research shows that the sandstone reservoir in the study area develops a diversified pore system. Residual intergranular pores and intergranular dissolution pores constitute the main reservoir space. The pores exhibit low cement filling degree and minimal matrix content.

Keywords

Ordos Basin; Tight Sandstone; Pore Structure; Physical Properties; Chang 6 Member.

1. Introduction

The Ordos Basin, as an important energy base in China, has seen its Upper Paleozoic tight sandstone reservoirs become key targets for oil and gas exploration and development. Among these, the Chang 6 oil-bearing formation, as one of the main producing zones in the basin, is renowned for its typical low-porosity and low-permeability characteristics. Its complex pore structure and physical properties directly influence hydrocarbon storage capacity and development efficiency[1-2]. Located in the central Yishan Slope of the basin, the Antaolin area has yielded significant discoveries in recent years regarding its Chang 6 reservoir. However, constrained by intense diagenetic alteration, the reservoir exhibits strong heterogeneity and complex, variable pore structures, which hinder efficient hydrocarbon development.

Previous studies have shown that the storage performance of tight sandstone reservoirs is primarily controlled by the combined effects of sedimentary microfacies and diagenesis, with significant correlations existing between microscopic pore-throat characteristics and macroscopic physical parameters. However, for the Chang 6 reservoir in the Antaolin area, existing research has mostly focused on the distribution of sedimentary facies belts or macroscopic physical property analysis, lacking in-depth understanding of the microscopic pore structure system and its controlling mechanisms on seepage capacity[3-5]. Particularly under the background of strong carbonate cementation, the pore evolution patterns in different diagenetic facies belts and their modification effects on reservoir quality remain unclear[6].

This study focuses on the Chang 6 sandstone reservoir in the Antaolin area, employing comprehensive experimental methods such as casting thin sections, scanning electron

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microscopy, high-pressure mercury injection, and nuclear magnetic resonance to address the following key issues: (1) the spatial configuration relationships of petrological characteristics in the reservoir and their controlling factors; (2) the modification mechanisms of multi-type cement distribution on pore structure. The research results will not only provide a theoretical basis for reservoir quality evaluation and sweet spot prediction in the study area but also offer important references for the effective development of similar tight sandstone reservoirs.

2. Regional Geological Context

The study area is located in the Antaolin (also spelled An Tiao Lin) region of the Zhidan oilfield, in the southern Ordos Basin. Geologically, Ordos is a relatively stable, craton-type multi-cycle basin[7-8]. It is the second-largest sedimentary basin in China, and its stratigraphy can be divided broadly into two systems: Phanerozoic marine carbonate (Paleozoic) and terrestrial clastics (Mesozoic). The overall structure of the basin is a gentle monocline that tilts eastward; local high (nose-shaped uplifts) and lithologic traps are also present. Tectonically, Ordos can be subdivided into units such as the North Shaanxi Slope, Weibei Uplift, Qilitan uplift, etc. The Zhidan area lies in the central part of the North Shaanxi Slope structural unit, near the Chang 6 production area.

The Chang 6 Member (Yanchang Formation, Triassic) is a principal oil-bearing interval in Ordosscirp.org. In the Antaolin area, the Chang 6 is interpreted as being deposited in a delta-front environment with abundant submarine distributary channels. The sand bodies are typically fine-grained and arkosic, reflecting derivation from nearby basement rocks. The reservoir lithologies are mainly feldspathic sandstone (often referred to as arkose) and subordinate lithic-feldspathic (lithic arkose) sandstone. Interbeds of siltstone and mudstone occur but the focus is on the reservoir sand bodies. The reservoir shows pronounced heterogeneity. Core and logging data indicate porosity is broadly low; porosity values cluster in the 8–12% range with an overall mean of about 9.4%. Permeability is likewise very low, typically from 0.02 up to a few millidarcies, with the main peak of permeability around 0.1–1.0 mD (mean ~0.22 mD). These properties classify the Chang 6 sandstone as a typical tight reservoir. Nonetheless, oil shows (fluorescence, oil staining) in the cores indicate that the sandstones do contain hydrocarbons, motivating detailed reservoir characterization.

3. Reservoir Fundamental Characteristics

3.1. Petrological Characteristics

Quantitative petrographic analysis of 83 core samples was performed to determine mineralogical composition (Figure 1). The results show that detrital components dominate the rock volume (58–97%, averaging 86.8%). Among the detrital fraction, K-feldspar and plagioclase together form the major component (22–65%, mean 49.9%). Quartz is the next most abundant detrital mineral (13–49%, mean 24.4%). Rock fragments (lithic grains) are less abundant (0–25%, mean 9.1%), and clay/minor flakes (including muscovite or biotite) are least (0–15%, mean 3.6%). In folk' s classification terms, these are predominantly feldspar-rich sandstones (arkoses) and feldspathic litharenites. This composition implies relatively short transport distance or rapid deposition from feldspar-bearing source rocks.

The petrographic data indicate that feldspar sandstones (arkose) and lithic-feldspar sandstones are the main reservoir rock types, consistent with previous studiesscirp.org. The abundance of feldspar suggests that reservoirs are potentially sensitive to chemical alteration (feldspar is less stable than quartz). The relatively low quartz content (~24% on average) also reflects the lithological makeup of the source terrain. Lithic fragments derive from igneous and metamorphic basement, quartzites, schists, etc., as thin-section observations show.

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Cementation is significant and complex. In the Chang 6 sandstones, total cement (matrix and pore-filling) ranges from 3% to 41% of rock volume (average ~12.7%). Carbonate minerals are the principal cements, including calcite, ferroan calcite, dolomite, and siderite. Clay minerals (notably chlorite and illite) also occur as authigenic cements and grain coatings. Minor amounts of siliceous (chalcedony/opal) and K-feldspar cement are present. Specifically, calcite content varies widely (0–30%, mean ~4.0%), ferro-calcite (ankerite) 0–25% (mean ~0.88%), dolomite 0–10% (mean ~0.19%), and siderite 0–14% (mean ~0.64%). Among clays, chlorite ranges 0–11% (mean 2.21%) and illite 0–13% (mean 1.70%). These cements together occupy the pore spaces to varying degrees. Notably, chlorite is the most common clay and often forms grain-rimming coatings or pore-lining aggregates. Such chlorite coatings can inhibit quartz cementation and thus help preserve porosity, but can also reduce effective pore throat size.

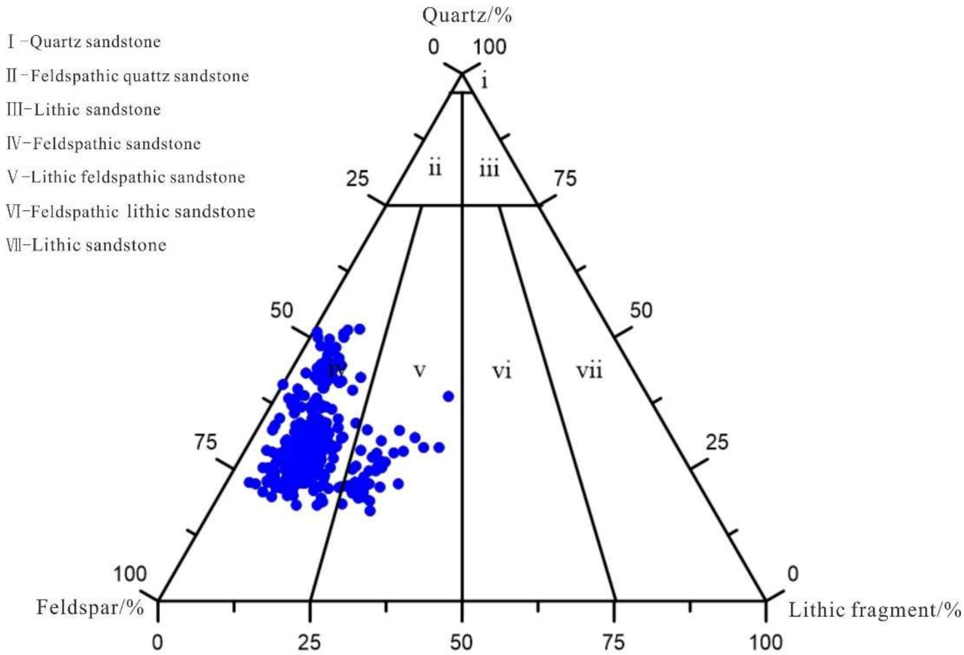

Figure 1. Rock and mineral types of Chang 6 reservoir in the study area

3.2. Pore Structure Characteristics

Microscopic examination (core thin sections and SEM) combined with porosimetry reveals that the Chang 6 reservoir has a multi-modal pore system. Six primary pore types are identified: (1) residual intergranular pores (primary, between grains); (2) intergranular dissolution pores (enlarged by chemical dissolution of unstable grains or cement); (3) intragranular (intraparticle) dissolution pores (within detrital grains, e.g. feldspar dissolution); (4) moldic pores (after dissolved fossils or porphyroblasts); (5) intercrystalline pores (between authigenic clay or carbonate crystals); and (6) microfractures. Of these, the residual intergranular and intergranular dissolution pores constitute the principal hydrocarbon storage space (Figure 2). In our samples, most pores are found at grain contacts or along grain margins. The SEM images (Figure 2) show that many residual pores are lined with thin rims of chlorite. These grain-edge chlorite coats are relatively thin but pervasive. Chlorite rims can help stabilize pore structure by preventing compaction and quartz cementation, thus preserving intergranular porosity. However, if chlorite is partially dissolved or altered (as seen in some SEM images), the pore boundaries become less distinct and porosity can be further compromised (Figure 2).

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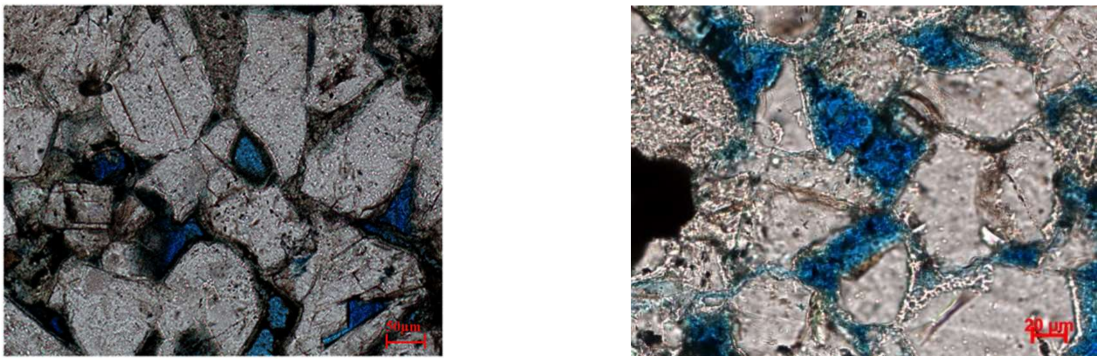

a. Residual intergranular pores with well-developed chlorite grain coatings and intragranular dissolution pores, Well Yong 287, 1411.21 m, Chang 6 Member.

b. Residual intergranular pores with chlorite grain coatings showing indistinct pore boundaries due to dissolution/alteration, Well Yongtan 9, 1354.65 m, Chang 6 Member.

Figure 2. Characteristics of intergranular pores in Chang 6 Member reservoir sandstones, study area

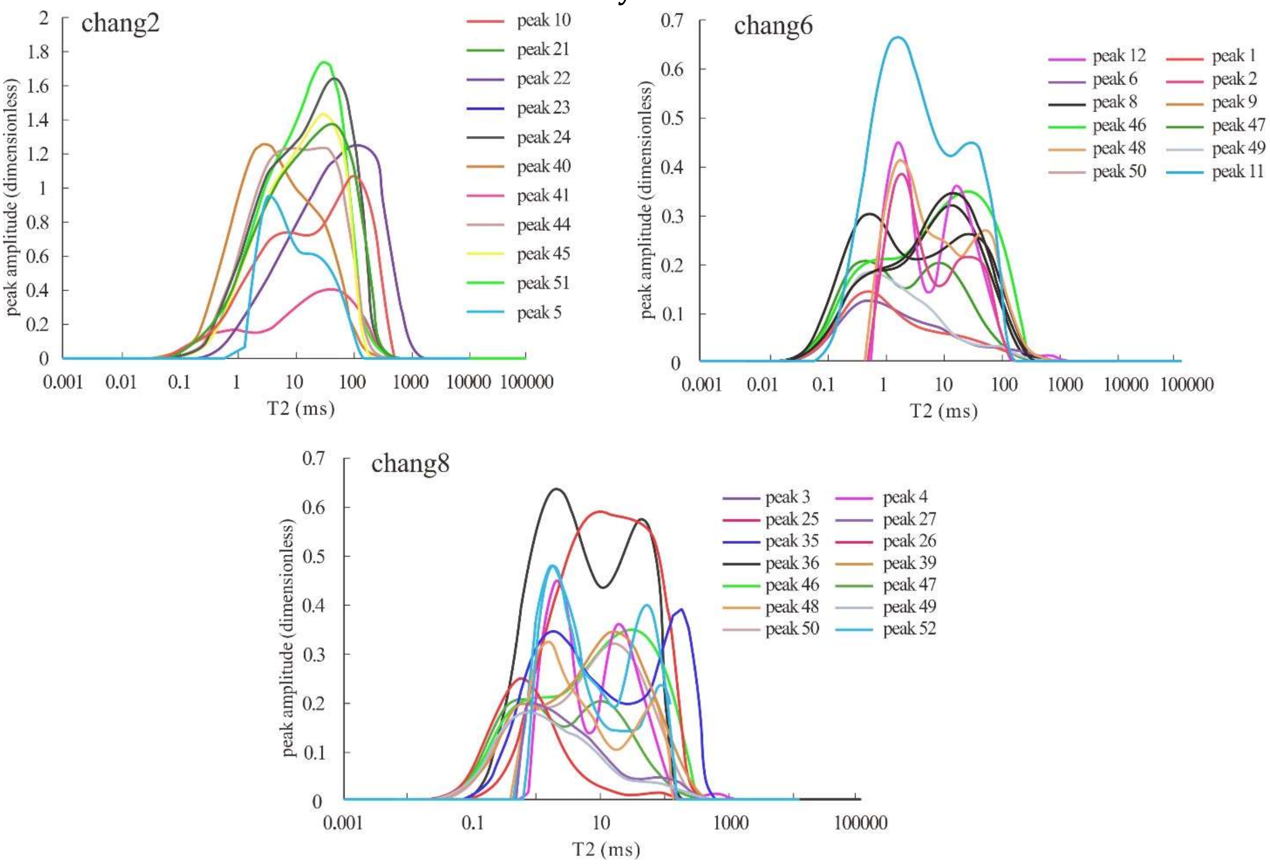

Figure 3. Spectrum Pore Structure Test Results of Chang 6 Member Sandstone

Pore throat size distribution was characterized by NMR T_2 relaxation spectra and MIP data (Figure 3). The NMR T_2 measurements indicate a wide variety of spectral shapes, reflecting multiple pore size populations. Several types of T_2 spectra were observed, including single-peak distributions, left-skewed single peaks, right-skewed single peaks, and multiple-peak spectra with biases. A typical single-peak sample shows a symmetric bell-shaped T_2 spectrum, indicative of a relatively homogeneous pore size distribution. By contrast, reservoirs exhibiting

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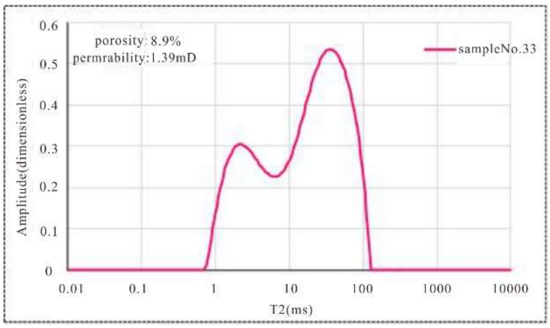
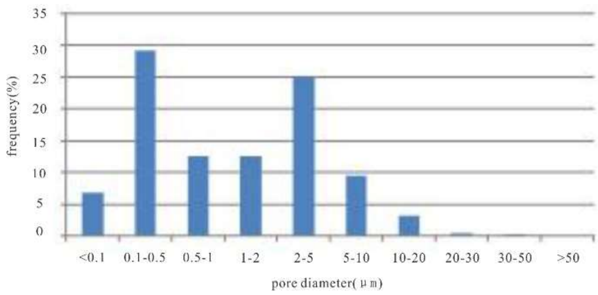
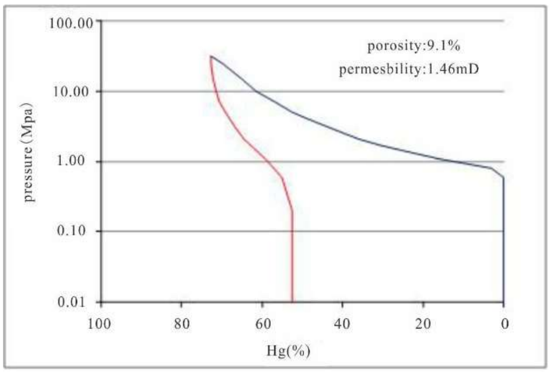
a "double-peak (right-skewed)" T_2 spectrum have two or more distinct peaks, with the larger-pore (longer T_2) peak dominating over the small-pore peak. This spectral type corresponds to reservoirs with significantly degraded petrophysical quality: both porosity and permeability decrease substantially, with porosity suffering the larger reductionFor example, in a representative well sample with a double-peak T spectrum (Figure 4), we find that the largest pores (>10 µm) comprise only about 3.96% of the pore volume, the 5–10 µm pore fraction about 9.44%, whereas micropores (<1 µm) account for ~48.73% of the volume. In other words, the reservoir evolves from a more balanced multi-scale porosity system to one heavily dominated by very small pores. Mercury injection data for this sample confirm a severely deteriorated throat network. The displacement (entry) pressure is as high as 4.36 MPa and median capillary pressure 0.7417 MPa. The maximum throat radius measured is only ~1.01 µm, with a median throat radius of about 0.17 µm. The throat sorting coefficient is low (0.197) and skewness high (1.533), indicating a very poor sorting and a strong skew toward fine throats. These pore-throat characteristics imply that fluid flow is extremely restricted: the tiny pore spaces and narrow throats necessitate high pressures for hydrocarbon displacement.



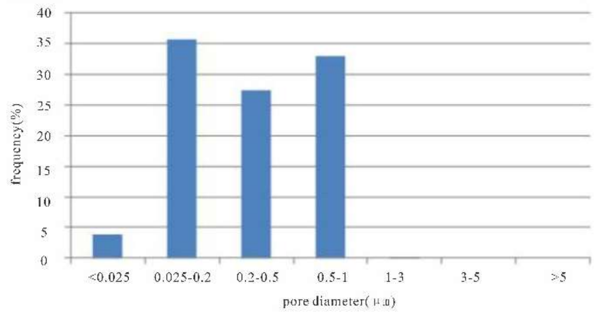
NMR T2 Spectrum Characteristics



Statistical Chart of Pore Size Distribution from NMR Measurements



Characteristics of Mercury Intrusion Curves



d. Statistical Chart of Pore Throat Radius Distribution from Mercury Intrusion Testing

Figure 4. Bimodal Right-Skewed NMR T2 Spectrum Pore-Throat Radius Analysis of Yanchang Formation Sandstone Reservoir (Well Yong-805, Chang 6 Member, 1483.77 m)

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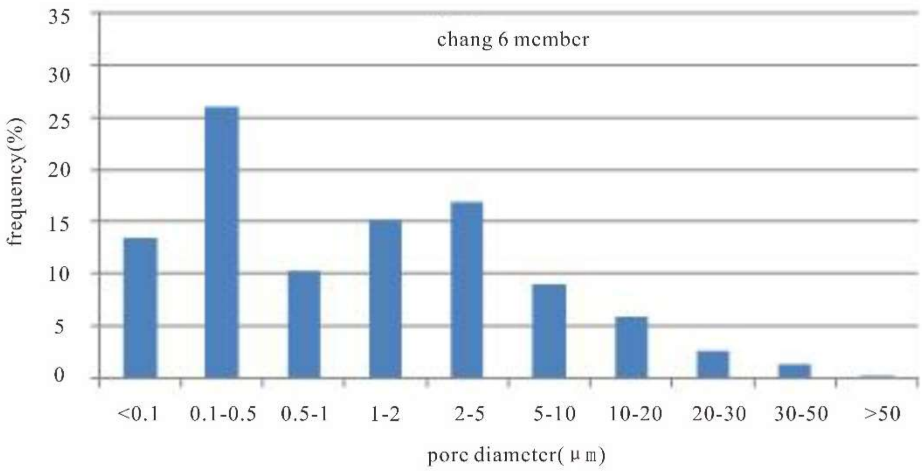

Figure 5. Comparison Chart of Pore-Throat Size Distribution in Sandstones of the Yanchang Formation in the Study Area

In general, the pore size distribution in the Chang 6 reservoir shifts towards finer pores with reservoir deterioration. Across the study area, only about 0.26% of total pore volume is in mesopores (10–50 μm), whereas >80% of pores are <10 μm; notably ~49–50% of pores are <1 μm. Pores of 1–10 μm ("fine" pores) make up roughly 41% of the distribution, with 5–10 μm pores ~9% and 2–5 μm pores ~17% of the volume. The dominance of submicron pores and scarcity of large pores is a clear indication of extensive dissolution of former pore spaces and compaction, leaving only small secondary porosity(Figure 5).

3.3. Reservoir Physical Properties

Core-based measurements of porosity and permeability and well logs were used to characterize the reservoir' s petrophysical properties and their spatial distribution. The porosity in the Chang 6 Member ranges widely from about 1.2% up to 22.1%, but is concentrated mainly between 4% and 16%. A clear peak in frequency occurs in the 8–12% porosity bin, consistent with the mean porosity of ~9.4%. Permeability is uniformly very low, mostly between 0.02 and 3.16 mD, with the main cluster in the 0.10–1.00 mD range. The average core permeability is ~0.22 mD.（Figure. 6 ） These overall statistics confirm that Chang 6 sandstones are tight by conventional standards: typical reservoir zones have porosity <12% and perm <1 mD.

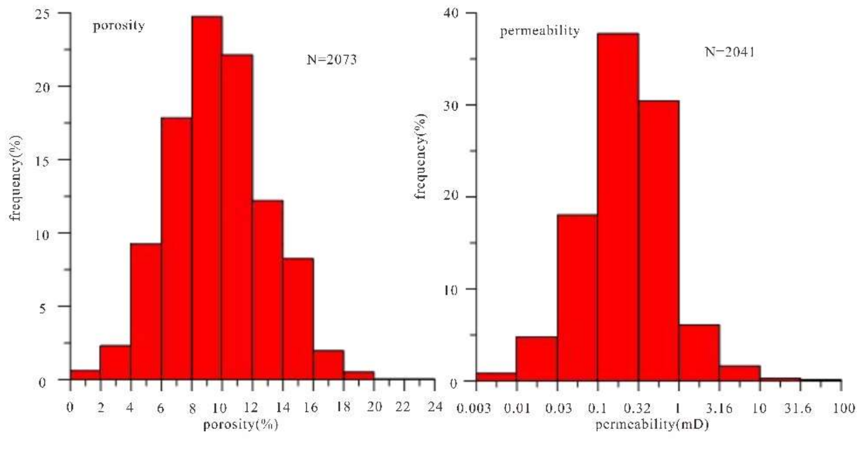

Figure 6. Statistical Chart of Porosity and Permeability of the Chang 6 Member Reservoir Sandstones in the Study Area

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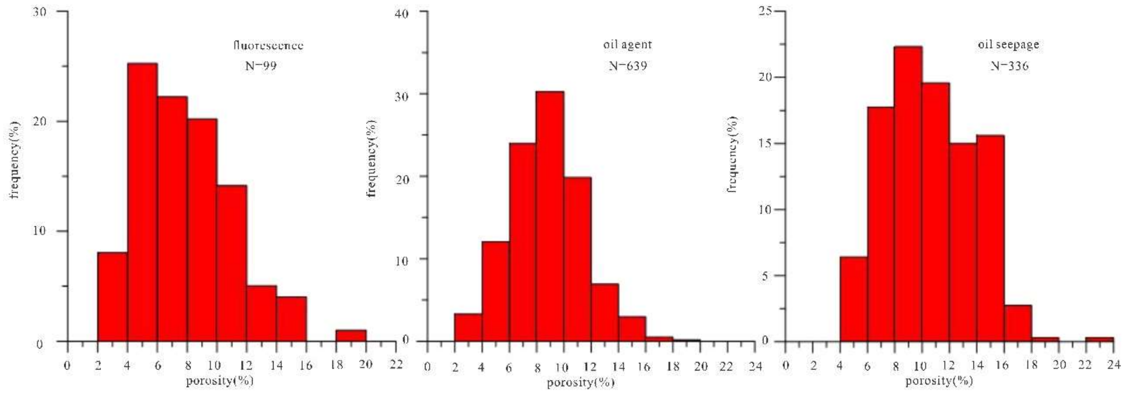

Figure 7. Statistical Chart of Porosity of Sandstones with Different Oil and Gas Show Levels in the Chang 6 Member Reservoir, Study Area

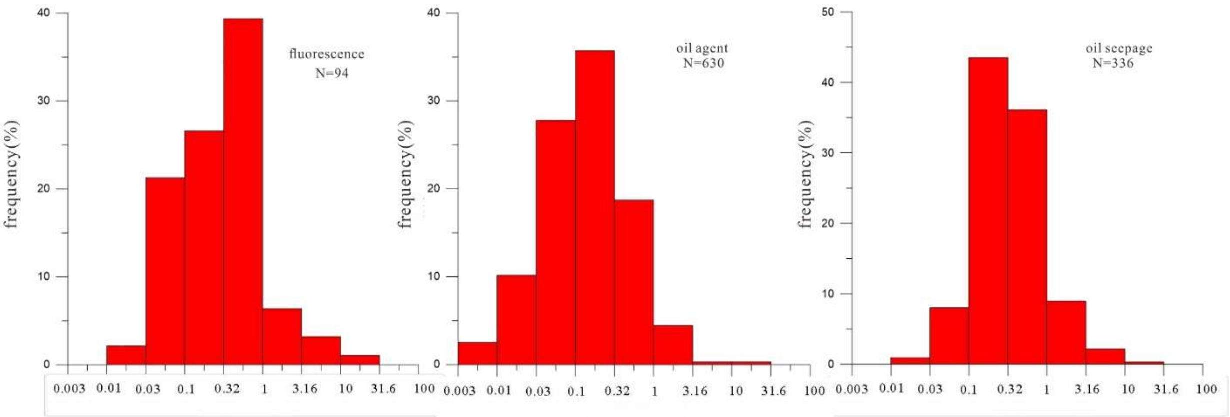

Figure 8. Statistical Chart of Permeability of Sandstones with Different Oil and Gas Show Levels in the Chang 6 Member Reservoir, Study Area

Reservoirs with varying hydrocarbon shows exhibit distinct petrophysical characteristics. Specifically, fluorescence-show sandstones have a porosity range of 2.5% to 18.3%, predominantly concentrated between 4.0% and 12.0%, with an average porosity of 7.1% (Figure 7); their corresponding permeability ranges from 0.02 to 12.15 mD, peaking between 0.32 and 1.0 mD, with an average permeability of 0.28 mD (Figure 8). Oil-stained sandstones show porosity variations between 2.7% and 18.4%, mainly distributed from 4.0% to 12.0%, averaging approximately 8.8%; their permeability ranges from 0.006 to 3.16 mD, primarily varying between 0.01 and 1.0 mD, with an average of about 0.20 mD (Figure 8). Oil-patch-show sandstones exhibit porosity variations from 4.5% to 22.1%, averaging around 10.1%; their permeability ranges between 0.02 and 25.16 mD, with most samples exceeding 0.1 mD, peaking approximately between 0.1 and 1.0 mD, and averaging about 0.35 mD (Figure 8).

4. Conclusion

The reservoir rocks are mainly feldspathic sandstones (feldspar-rich) and lithic arkoses, with detrital grains accounting for more than 85% of the rock volume. The cements are well developed, particularly carbonate minerals (calcite/ferroan calcite, dolomite, siderite) and clay minerals (chlorite, illite), and chlorite grain coatings are universally present. These cementation processes significantly reduce intergranular pores and profoundly influence the pore structure.

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There develop six types of pores - residual intergranular pores, intergranular dissolution pores, intragranular dissolution pores, moldic pores, intercrystalline pores, and microfractures, among which residual intergranular pores and intergranular dissolution pores constitute the main reservoir space. However, the pore connectivity is moderately poor, with numerous pores being isolated by cements. NMR/MICP data show developed micropores: large pores (>10μm) are nearly negligible (<4% pore volume), while micropores (<1μm) account for about half of the pore space.

The overall porosity and permeability are extremely low (average porosity 9-10%, permeability 0.2-0.3mD), with a distinct porosity peak occurring in the 8-12% range. The intervals with better hydrocarbon shows exhibit slightly higher porosity and permeability, but all are classified as tight reservoirs by conventional standards.

References

[1] Davarpanah A, Mirshekari B. Sensitivity analysis of reservoir and rock properties during low salinity water injection[J]. Energy Reports, 2019, 51001-1009.

[2] ZOU Caineng, QIU Zheng. Preface: New advances in unconventional petroleum sedimentology in China[J]. Acta Sedimentologica Sinica, 2021, 39(1): 1-9.

[3] FAN Yang. Sensitivity evaluation and stimulation optimization of ultralow permeability sandstone reservoir[J]. ACS Omega, 2023, 8(40): 37176-37185.

[4] LIU Zhongquan, SHI Bingbing, GE Tianchen, et al. Tight sandstone reservoir sensitivity and damage mechanism analysis: a case study from Ordos Basin, China and implications for reservoir damage prevention[J]. Energy Geoscience, 2021, 3(4): 394-416.

[5] FAN Pingtian, LIU Yuetian, LI Ping, et al. Reservoir sensitivity analysis of tight sandstone and its controlling factors: a case study from Chang 4+5 to Chang 6 reservoirs in N 212 Well Block of Nanniwan Oilfield, Ordos Basin[J]. Geofluids, 2023, 8878837: 1-16.

[6] ZHAO Liping, LI Zubing, FU Liangliang, et al. Characteristics and main controlling factors of He 8 Member reservoir in the middle of Block Su75. Ordos Basin, 2025, 32(1):88-95.

[7] YANG Fei, LIU Juanxia, SUN Yanqi, et al. Characteristics and control factors of effective reservoirs in Mesozoic volcanic buried hill of the Bohai Sea area[J]. Journal of Xi' an Shiyou University(Natural Science Edition), 2025, 40(2): 33-41.

[8] ZHOU Chenghan. Tight sandstone reservoir evaluation of Shahezi formation in the Lishu fault depression[D]. China University of Petroleum(Beijing), 2023.