Research Article

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The impacts of diagenetic facies on reservoir quality in tight sandstones

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Abstract: The impact of diagenetic minerals and the characteristics of pore structures on reservoir qualities has been studied separately in the past years. However, the difference in the reservoir quality with different pore structures and having same or similar content of diagenesis minerals has not been ascertained. In this study, based on the core samples derived from Chang 6 member in the Ordos basin, various tests were performed to examine the sandstone diagenesis and investigate the pore structure. The results showed that there were five diagenetic facies by diagenetic and pore structure analyses, and the best reservoir quality rocks were found to have relatively low percentage of illite, carbonate cement, pore-filling chlorite, authigenic quartz, and relatively high proportion of intergranular pores. Smectite-to-illite reaction and chemical compaction were main sources for quartz cementation at 60–120°C, and carbonate content was found to increase toward source rocks. The porosity depth trends significantly affected the diagenetic facies. The diagenetic and the pore structure pathways of various diagenetic facies were reconstructed by integrated petrographic, mineralogical, and pore system data. This study provides insights into the porosity evolution and diagenetic pathways of various diagenetic facies of tight

sandstones, and the influence of diagenesis minerals and pore structures on their reservoir quality.

Keywords: diagenesis, pore structure, diagenetic facies, tight sandstone, Yanchang formation, Ordos Basin

1 Introduction

The Upper Triassic Yanchang Formation is one of the most important unconventional stratigraphic units in Ordos Basin, China, where widely distributed hydrocarbons in major petroliferous members [1–3]. Several studies reported on depositional environment, tectonic setting, diagenesis, pore structure, and reservoir quality [4–8]. These studies confirmed that the Yanchang Formation had advantageous sedimentary facies for oil accumulation, and the hydrocarbon sources were distributed widely in the basin [9,10]. The reservoir in Chang-6 (the sixth member of the Yanchang Formation) was defined as a tight sandstone reservoir with a helium porosity not more than 10% and air permeability not more than 1 mD. The strong microscopic pore structure might hinder the successful accumulation of petroleum due to narrow throats and deteriorating pore–throat connectivity [11]. The pore structure was considered as one of the main factors influencing the production performance of tight sandstone reservoir reserves [12–14]. Diagenetic alteration influenced the pore structure progressively [11,15]. As a result, it is vital to have a detailed understanding of the diagenetic alteration and its impact on pore structure for better assessment of reservoir quality [2,16]. Although there are uncertainties related to mechanical compaction and cementation processes that dominate the pore structure, extensive diagenetic alteration and pore structure complexity present exploration and development risks [2,9,17–19]. Burial history, diagenetic evolution, pore volume evolution, the mechanism of oil accumulation and pore structure, and their effect on reservoir quality are still being debated by scholars in different sedimentary basins [12,18,20,21].

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In this study, we aim to (a) describe the composition of Chang-6 sandstone reservoir; (b) perform a detailed diagenetic and pore system analysis; (c) describe the different diagenetic facies; (d) analyze the source of quartz and carbonate minerals; (e) investigate the timing of diagenetic processes and reconstruct the diagenetic history; and (f) estimate the effects of diagenetic alteration and pore structure on the reservoir quality for various diagenetic facies for the Chang-6 sandstone reservoir. This multidisciplinary study will help understand the characterization of diagenetic evolution and pore structure and highlights the impact of diagenetic facies on reservoir quality of such sandstones. To distinguish this research from other published studies in this basin, we inverse the current pore structures by verifying the diagenetic evolution and comparing the pore network and mineral appearance in different diagenetic facies. Furthermore, these results also help to understand the genetic mechanism, future exploration, and development of the Chang-6 sandstone reservoir and can be used in similar tight sandstones.

2 Geological setting

The Ordos Basin lies to the west of Taihang Shan Mountain, and it occupies most of the Shaanxi Province and Ningxia Province in Northwest China and can be further subdivided into six first class tectonic zones, namely, the Yimeng Uplift Zone, the Jinxi Fault-Fold Belt Zone, the Weibei Uplift Zone, the Tianhuan Depression Zone, the Xiyuan Thrust Belt Zone, and Shanbei Slope Zone (Figure 1(a), [4,22]). The core plug samples used in study are taken from Huachi Area located in the Shanbei Slope Zone and the Tianhuan Depression Zone, and this area is also the most oil-bearing zone in Ordos Basin (Figure 1).

The Yanchang Formation in Ordos Basin is in conformable contact with the underlying Middle Triassic Zhifang Formation, while it is in an unconformable contact with the overlying Lower Jurassic Fuxian Formation [3]. Due to continual fluctuations in lake levels during the Late Triassic, the Yanchang Formation stratigraphy has many reservoir rocks, seal rocks, and source rocks and is the main oil-producing formations in the Ordos Basin [23]. The formation can be subdivided into ten members based on lithological combination, electrical characteristics, and depositional cycles (Figure 2, [13]). Among these, the majority of Chang-7, the top of Chang-4+5, and the top of Chang 9 are dominantly mudstones, siltstones, and shales and are sources of hydrocarbons. The entire Chang-1, the

majority of Chang-4+5, the bottom of Chang-7, and the top of Chang-8 are dominantly mudstones and shales and are sealing units. In contrast, the majority of Chang-2 and Chang-6, the middle of Chang-8, the top of Chang-3, and the bottom of Chang-4+5 are mainly composed of fine to medium-grained sandstones interbedded with mudstones, which were the main reservoir units in the Yanchang Formation (Figure 2, [13]).

The sixth member of Yanchang Formation (Chang-6), shown in Figure 2, was mainly controlled by the southwest and northeast provenance. The depositional facies of the Chang-6 Member in the Ordos Basin have been studied by many researchers [2,24,25], who believe that the sedimentary environment of the Chang-6 Member could be interpreted as the meandering delta in the northeast, while the braided delta developed in the southwest and the middle of Ordos Basin was dominated by the lag deposits [26]. According to the petroleum systems analysis, the seventh member of the Yanchang Formation (Chang-7), which underlies Chang-6, is the main source rock of the Yanchang Formation, and the mudstones and siltstones layers within the Chang-4+5 source rocks act as the seal for the Chang-6 reservoirs [9]. The efforts driving the hydrocarbon for migration and accumulation of hydrocarbons in tight reservoirs of the Chang-6 Member in the Ordos Basin are mainly buoyancy and overpressure associated with compaction disequilibrium [27]. The source rocks are dominated by type II and III kerogens, having a total organic carbon content mainly greater than 1.0 wt% but less than 10.0 wt% with vitrinite reflectance of 0.5% and are generally present in the oil window [28–30]. The reservoir quality is considered as one of the major controls on petroleum reserves in this area [1,31].

3 Samples and methods

Nine hundred and forty-five nonfractured blocks and nonweathered core samples were collected from 143 wells. All core plug samples, horizontally parallel to the bedding plane, were regular cylinders (with 5.0 cm in length and 2.5 cm in diameter). The residual bitumen was removed with a mixture of alcohol and chloroform and then dried at 130°C for 24 h before the experiments. Before beginning the experiments, the helium porosity and nitrogen permeability, used for the routine core analysis, were acquired from 1,314 core plug samples with 12,020 data points, using an FYK-I apparatus under an ambient pressure of 20 MPa.

Figure 1: (a) Location map of the research area in the Ordos Basin (modified after [4,22]) and (b) location map of wells in research area (modified after the materials from Changqing Oilfield, China).

To study the petrology of the samples and to differentiate the different types of interstitial minerals and pore spaces, 1,100 representative thin sections (no artificial fracture and induced holes) were ground to approximately 0.03 mm and impregnated with red epoxy, Alizarin Red S and K-ferricyanide, and then examined using a Zeiss Axioskop II microscope. All the thin sections were point counted (300 points per sample) for petrographic, diagenetic, and pore type analysis. Four hundred representative samples were coated with a thin layer of gold and examined with FEI Quanta 400 FEG scanning electron microscope (SEM). In addition, 95 core samples were viewed under a Gatan MonoCL³⁺ cathode luminescence spectrometer with 20 kV acceleration voltage.

Two hundred and eleven samples were analyzed for clay fraction mineralogy by an energy-dispersive X-ray spectrometer (OXFORD IE 350) and then calculated the content of clay-mineral species using X-ray diffraction (XRD). Before the experiments, each sample was ground into powder from, dried, and mixed with ethylene glycol. Then, all the samples were heated to over 500°C for at least 2.5 h.

Based on the petrological studies, 216 samples were selected for traditional mercury intrusion porosimetry

(MIP) experiments. MIP tests were performed in a Micromeritics Autopore IV 9420 Instrument with the pressure maintained up to 200 MPa, corresponding to a pore radius of about $3.6 \times 10^{-3} \mu\text{m}$, which satisfied the Washburn equation (1921) [32]. We offer a simple procedure of MICP based on previous studies [33,34]: the contact angle between mercury and the void surface was assumed to be 140° and interfacial tension of mercury was set to 0.48 J/m^2 . First, the samples were placed in the sealed apparatus where the air was evacuated and replaced by mercury through the low pressure port. Next, the mercury that filled the chamber and samples was removed from the low-pressure port. Thereafter, mercury was injected using a high-pressure port. Drainage and imbibition related data were collected by during the experiment.

Fluid inclusion analyses and homogenization temperature (T_h) tests of 55 samples were conducted using Linkam THMSG-600 heating and cooling stage. The temperatures of phase transitions between -180°C and 500°C , with $\pm 1^\circ\text{C}$ precision when the temperature was higher than 40°C and the determination of transitions was less than 40°C , are accurate to $\pm 0.1^\circ\text{C}$. A Zeiss Axioskop II microscope was used to identify trapped

Figure 2: Generalized Triassic-Jurassic stratigraphy of the Ordos Basin (modified after [13]).

minerals and gases. Fluid inclusion composition and density could be calculated as per Diamond et al. (2010).

Fifty-one sandstone samples were selected for carbon and oxygen stable isotope analyses under a Thermal Fisher Argus VI isotope ratio mass spectrometer. First, the samples were ground into powder and flushed with ultrapure He gas. Then, the powder was mixed with 100% orthophosphoric acid and heated to 700°C for 2 h. Finally, carbon dioxide was passed for measuring the isotopes. Carbon and oxygen isotope tests were based on the Pee Dee Belemnite (PDB) standard and the standard mean ocean water, respectively.

This article is organized as follows. The petrographic mineralogy, physical properties, and typical diagenesis are described in Sections 4.1, 4.2, and 4.3, respectively. Pore systems and diagenetic facies characteristics are described in Sections 4.4 and 4.5, respectively. Source of cements and timing of diagenetic facies are presented in Sections 5.1 and 5.2. The behavior of different diagenetic facies (pore structure evolution) is presented in Sections 5.3 and 5.4.

4 Results

4.1 Petrographic mineralogy

Lithologic investigation of the Chang-6 tight sandstones in the Huaqing area showed that the detrital components comprised 20.0–74.8% quartz (mean 42.42%), 5.1–70.5% feldspathic fragments (mean 39.2%), and 3.5–53.1% rock fragments (mean 18.4%), indicating that the sandstones could be classified as lithic arkose, arkose, feldspathic litharenites, and few litharenites according to the scheme of Folk (1980; Figure 3(a)). The quartz grains were mainly monocrystalline. The feldspars included plagioclase and K-feldspar. The rock fragments mainly consisted of metamorphic rocks and sedimentary rocks, with minor volcanic rocks. The mica contained 0.2–9.2% muscovite with an average of 2.8% and trace amounts (<1%) of biotite and mica.

The particle size analysis revealed that the sandstones ranged between fine and very fine-grained, sorting between poor and well sorted, while the roundness was mainly subangular, with few angular and subrounded (Figure 3(b and c)). Grain contacts were dominated by planar contacts, as well as pointed contacts, while some samples showed concave–convex contacts. Microscopic fractures could also be found. The matrixes were mainly composed of illite, ferrocaltite, ankerite, chlorite, and authigenic quartz, with average proportions at 6.9%, 2.6%, 2.0%, 1.8%, and 1.2%, respectively. Trace levels of pyrite, siderite, laumontite, kaolinite, and anhydrite were also detected.

4.2 Porosity and permeability

The physical properties of Chang-6 formation sandstones were relatively poor. The helium porosity varied between 0.45% and 23.10% with an average of 9.64%. Horizontal air permeability varied between 0.001 and 67.106 mD (the core samples with permeability over 10 mD had artificial or natural fractures) with an average of 0.242 mD, indicating that the Chang-6 sandstones had observed values lower than the typical tight sandstone. The permeability and the porosity showed slight correlation ($R^2 = 0.6075$). The core samples with low porosity and relatively high permeability were caused by the development of micro-cracks (Figure 4).

Figure 3: (a) Classification of sandstone after Folk's (1980) [35] criterion, (b) sorting distribution, and (c) roundness distribution of Chang-6 tight sandstones.

4.3 Diagenesis and authigenic mineralogy

The Chang-6 sandstones had undergone significant diagenetic processes, including mechanism compaction, cementation by clay minerals, carbonate, euhedral quartz and some other minor cementation types, and dissolution (mainly feldspar). Ankerite, clay minerals (illite, illite–smectite mixed layers, and chlorite), and authigenic quartz were the main pore-filling interstitial constituents; however, others such as siderite were rarely observed.

4.3.1 Quartz

The authigenic quartz was one of the most common cement types in the sandstones responsible for the deterioration of the reservoir quality. The content of quartz cements between trace amount and 8.8%,

occurring in two different types of morphologies in the study area. The first type occurred as euhedral, syntaxial overgrowths with concave–convex contacts, which extend dust rims around the detrital grains (Figure 5(a)). However, the SEM clearly showed the characteristics of the authigenic quartz overgrowth, where the authigenic quartz, engulfed by other minerals such as chlorite and illite, occurs in pores as euhedral crystals. The crystal and the size of detrital quartz were relatively large with shell-like fracture in SEM images (Figure 5(b)). The CL images showed that the detrital grain was bright, while the authigenic clay was dark (Figure 5(c)).

4.3.2 Ferrocalcite and ankerite

Ferrocalcite and ankerite were found to be two of the major carbonate cement types, which occluded the pores in the Chang-6 sandstones, ranging from trace amounts to 49.0% with an average of 2.5% and from trace amounts to 34.2% with an average of 1.3%, respectively. The carbonate that had a profound impact on reservoir quality showed a homogeneous orange appearance in CL images (Figure 5(c)). Ferrocalcite and ankerite were the second generation of calcite and dolomite with ferroan composition, while the first generation of both had nonferroan composition, indicating dominantly micro-crystalline carbonate (<100 μm) instead of the feldspars and block large intergranular pores and is rarely seen in the study area. The ferrocalcite and ankerite belonged to sparry carbonate (>100 μm), which occurred as euhedral

Figure 4: Porosity versus permeability of the core samples.

Figure 5: The characteristics of quartz cement, ferrocalcite, and ankerite cementation: (a) thin section observation from the quartz overgrowth and ankerite replacing feldspar; (b) honeycomb-like mixed-layer illite/smectite, chlorite, and authigenic quartz (SEM); (c) CL micrograph of detrital quartz (brightly luminescent) and authigenic quartz (darkly luminescent); (d) poikilotopic ankerite filling in small pores (thin section); (e) thin section observation from ferrocalcite and ankerite replacing the quartz and feldspar, occupying the intergranular pores and dissolution pores as well, the mica deformed as pseudomatrix; (f) micrograph of CL showing ferrocalcite filling intergranular pores and dissolution pores. QD, detrital quartz; QA, authigenic quartz; An, ankerite; I/S, mixed-layer illite/smectite; Fc, ferrocalcite; Fe, feldspar; Mi, mica.

rhombs and pore-occluding with local poikilotopic (Figure 5(d and e)). The sparry carbonate was considered as having mesodiagenetic origins, while the microcrystalline carbonate was suggested to be having eodiagenetic origins as it was engulfed by the latter's carbonate cements (Lai et al., 2015). The ferrocalcite and ankerite in the study area were mainly sparry carbonate type, which might either had replaced the feldspar (Figure 5(a)) or precipitated in feldspar dissolution pores (Figure 5(d–f)), indicating that the ferrocalcite and ankerite shaped during late-stage diagenesis.

4.3.3 Clay minerals

The XRD data indicated that the total amount of clay minerals in the Chang-6 formation ranged from 1.26% to 10.56%, with an average of 4.61%. The clay minerals in this section include illite (trace amounts to 7.94%, with average of 1.06%), chlorite (trace amounts to 4.44%, with average of 0.56%), and mixed-layer illite/smectite (trace amounts to 1.66%, with average of 0.26%). Kaolinite was rarely seen in the study area because of illitization or its initial absence (Figure 6(a)). Mix-layer

illite/smectite occurred in honeycomb texture, which blocked pores and throats. The proportion of over 85% illite indicates that $R = 3$ Reichweite order (Figure 5(b)). The hair-like illite blocked the primary pores and occasionally bridged the pores that significantly reduced the permeability (Figure 6(a–c)). The illite and mixed layer illite/smectite always engulf quartz cements

(Figure 5(b)). However, they form later than carbonate minerals (Figure 6(b, c)). The pore-lining chlorite grew tangentially to the surface of grains occur as needle and rosette-textured while grew before quartz cement and filled the pores in a rosette shape, which was associated with the quartz cement, indicating that certain amount of chlorite generated in the late diagenesis (Figure 6(d)).

Figure 6: The characteristics of clay minerals cementation and feldspar dissolution, with SEM micrographs showing: (a) illite and kaolinite cementation; (b) hair-like illite block the pores; (c) hair-like illite bridging the grains; (d) pore-lining and pore-filling chlorite; (e) feldspar dissolution; (f) framboid-like pyrite. Il, illite; Ka-kaolinite; PFCh, pore-filling chlorite; PLCh, pore-lining chlorite; FD, feldspar dissolution; Py, pyrite.

4.3.4 Feldspar dissolution

The thin sections and SEM images confirmed that the feldspars in Chang-6 sandstones dissolved into honeycomb shape (Figures 5(a, d, e) and 6(e)), which was susceptible to the influence of acidic fluids from the source rocks [35]. The development of secondary pores as a result of partial to complete dissolution was the major indicator of feldspar dissolution [35]. The content of feldspar dissolution in the study area was between 0.1% and 4.4%, with an average of 0.87%. The feldspar dissolution is associated with a filamentous illite, which indicates that the kaolinite commonly associated with feldspar dissolution was illitization [36,37].

4.3.5 Minor cements

Pyrite and feldspar overgrowths were the minor cements in the Chang-6 tight sandstones. The pyrite occurred as framboid and adjacent to carbonate and clay minerals (Figure 6(f)). Feldspar overgrowth occurred around detrital feldspar, while the line was dashed in black between them and usually corroded by ferrocaltite and ankerite (Figure 5(a and d–f)). Pyrite and feldspar overgrowths were much less commonly observed, occurring in no more than 0.5% of the sandstones.

4.4 The characteristics of pore system

4.4.1 Pore system by image analysis

Four types of pores, namely, residual intergranular pores, dissolved pores, intragranular pores, and few micro cracks, were observed in the Chang-6 tight sandstone reservoirs through thin section micrographs and SEM. The residual intergranular pores were polygonal in shape and largest (mainly 10–100 μm) and significantly reduced by mechanical compaction (Figure 7(a)). Dissolved pores were caused by acid and could enlarge the intergranular pores and produce new clay-related pores (Figures 4(a, d, e), 5(e) and 7(b)). The diameters of dissolved pores could be over 200 μm if connected with a primary intergranular pore. The pores between aggregated interstitial particles (such as clay minerals, carbonate, and authigenic quartz) were found

to be intragranular pores (Figure 7(c)), which were continuously distributed especially had high content of interstitial minerals, and were the main pore type due to cementation (Xiao et al., 2018). The micro cracks is subdivided into two parts, stress cracks induced by mechanical compaction and dissolved cracks induced by the acid flow through the inter particle path (Figure 7(d)).

4.4.2 Pore system quantitative assessment

Mercury porosimetry could indicate the relationship between external pressures and mercury saturation. This test could evaluate porosity, pore size distribution, pore throat radius, and other pore structure-related parameters. The intrusion and extrusion curve changed with an increase in the pressure. With an increasing in the displacement pressure (the point at which the mercury was first injected into the sample, P_d), the horizontal stages became negligible. This indicated that the pore throat sorting had a positive relationship with the lower displacement pressure in MIP tests. The plateau-like trend and exponential trend represented intergranular and intragranular pores in capillary curves, respectively. With the increase of permeability (Figure 8(a)), the length of plateau-like trend increased, indicating that the proportion of intergranular pores increased [38]. The P_d could be converted to an equivalent pore radius R_{max} , which represented the maximum radius in the samples, between 0.1 and 3.06 μm , while the most frequent ones varied from 0.2 to 0.6 μm with a nonuniform frequency distribution (Figure 8(b)). r_{50} is considered as a medium radius, which is at the 50% point of the capillary pressure converted to an equivalent pore radius, ranging between 0.04 and 0.24 μm (Figure 8(c)). The distribution of maximum injection saturation varied from 38% to 98% and was right skewed (Figure 8(d)), while the sorting coefficient varied between 0.4 and 2.6, with two distinct peaks at 0.4 and 1.2 (Figure 8(e)). The residual mercury saturation of mercury withdrawal was used to evaluate oil recovery, which varied between 67% and 85% and only a fraction of samples was lower than 60% (Figure 8(f)). The relative scattered distributions of all the parameters were indicated and the sandstones pore throat size of the sandstone was complex and heterogeneous, and no single pore system parameter could appraise the reservoir quality on its own.

Figure 7: The characteristics of a pore system: (a) thin section micrograph of intergranular pores; (b) thin section micrograph from dissolved pores; (c) SEM micrograph from intragranular pores; (d) SEM micrograph from micro cracks. Ie, intergranular pore; Di, dissolved pore; Ia, intragranular pore; MC, micro crack.

4.5 Source of cements

4.5.1 Source of quartz cements

There have been debates on whether the internal or external sources of quartz last for a long time [39–41]. There were no large faults in the Shanbei Slope in the Ordos Basin. Hence, there was no relationship between quartz and faults, indicating that long distance transfer of external SiO_2 (aq) into sandstones might be impossible [42]. The heterogeneity in porosity and permeability also made it hard for a significant shift of external SiO_2 (aq) into sandstones from proximate mudstones or shale [42,43]. Therefore, the external sources might be unimportant. Internal sources of silica could include chemical compaction, feldspar dissolution, biogenic silica, and transformation of clay minerals [44,45]. Biogenic silica could not have been a likely candidate because only a few biogenic silicas were observed in the Chang-6 sandstones in the Ordos Basin. A K-feldspar–kaolinite reaction would have been unlikely due to the absence of kaolinite in the study area. The micro concave–convex grain contacts were frequently observed, and detrital quartz and authigenic quartz were always accompanied by authigenic minerals, especially

illite and mixed-layer illite/smectite (Figure 6(c and d)). These phenomena indicated that the silica was mainly supplied from smectite-to-illite reaction and chemical compaction [46]. Apart from observation through thin section micrographs and SEM, homogenization temperatures of the aqueous fluid inclusions tests were conducted to account for the source of silica, and the results indicated that the quartz cement shaped in a continuous process from about 60°C to 120°C (Figure 9).

4.5.2 Source of carbonate

The sources of carbonate could be external, internal, or hybrid [47,48]. Bulk isotopic signatures of carbonate cements provided the clues to clarify the origin of carbonates. The $\delta^{13}\text{C}$ values of VPDB ranged from -7.2‰ to -1.6‰ , av. 3.0‰ and $\delta^{18}\text{O}$ values VPDB range from -10‰ to -25.6‰ , av. -19.3‰ (Figure 10(a)). The Keith equation (1964) [49] was used to identify the original pore water environment of the carbonate:

$$Z = 2.048 \times (\delta^{13}\text{C} + 50) + 0.498 \times (\delta^{18}\text{O} + 50)$$

$Z > 120$ was the characteristic of marine pore waters, while $Z < 120$ was the characteristic of fresh terrestrial

Figure 8: The intrusion/extrusion curves and parameters derived from MIP: (a) Capillary pressure curves for typical samples; histograms of (b) maximum pore-throat radius; (c) medium pore-throat radius; (d) maximum injection saturation; (e) sorting coefficient and (f) residual mercury saturation.

Figure 9: Histograms of aqueous inclusions of quartz versus homogenization temperature (T_h) in the Chang-6 tight sandstone reservoir.

waters. The Z value of all the samples was lower than 120, which meant that they were all characteristic of

fresh terrestrial waters (Figure 10(b)). The $\delta^{13}C$ values of VPDB of primary lacustrine carbonates ranged between -6‰ and -2‰ , indicating that the carbon was mainly attributed to the primary lacustrine carbonates (Kelts and Talbot, 1990). Also, the relatively low negative $\delta^{13}C$ values suggested that decarboxylation of organic matter in nearby mudstones or shales was another significant carbon source, and the CO_2^{3-} was derived from the mixture of carbon and terrestrial water [50,51]. Volcanic rock fragments and smectite-to-illite reactions were very common in the Chang-6 formation in the Ordos Basin, which were the main sources of Fe^{2+} , Mg^{2+} , and Ca^{2+} [52]. The carbonate values increased with the decreasing distance of samples to source rocks (Figure 10(c)), and Fe^{2+} , Mg^{2+} , and Ca^{2+} could have been expelled from source rocks to nearby sandstones [53], indicating that the source rock was another origin of those ions. When

Figure 10: The distribution characteristics of isotopes, Z value, and carbonate content: (a) $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ distribution; (b) Z value versus burial depth; and (c) carbonate content increase with the decreasing distance to source rock.

these ions would have diffused to the pore fluids, the carbonate would have precipitated when mixing with the CO_2^{3-} . Feldspar dissolution and illitization of kaolinite could have also provided some Ca^{2+} , which was another important Ca^{2+} source of carbonate cements [37].

5 Discussion

5.1 Multitype model of void space

To simulate the various types of void space, a multitype model was developed to simulate the pores between the detrital grains and the void space related to clay. According to Sakhaee-Pour and Bryant (2014), the pores between the detrital grains comprised intergranular pores (interparticle pores) and intragranular pores (clay-related pores), which were represented by the

network model and the treelike model, respectively (Figure 11(a and c)). The plateau-like trend in mercury intrusion curves represent intergranular pores, while the intragranular pores lead to an exponential trend of pressure and mercury saturation (Figure 7(a)). The shape of withdrawal curves of capillary pressure and the hysteresis degree could account for some phenomenon as well. A weak hysteresis and a low residual mercury saturation at almost zero capillary pressure indicated good connectivity of pores or a large proportion of intragranular pores (Figure 7(a)).

Clay-related pores were classified into three types based on the scale of pores, including intracrystalline pores within aluminosilicate layers, intercrystalline pores that represent the minor pores between clay particles, and clay aggregated pores [54,55]. The mercury would enter the largest pores (clay aggregated pores) first, then intercrystalline pores, and then the smallest intracrystalline pores (Figure 11(b)). The maximum pressure used in this study was 200 MPa, which could be converted to an equivalent pore radius of 3.6 nm and

Figure 11: Schematic diagrams of pore network model and clay-related model: (a) interparticle pores dominant model; (b) intragranular pores dominant model; and (c) treelike pores model. IPP, interparticle pores; IAP, intragranular pores.

larger than the radius of intracrystalline pores. Hence, only intercrystalline pores and clay aggregated pores were considered in this study. The features of clay-related pores and its impacts on drainage and imbibition of MIP tests could be interpreted by a treelike pore model according to Sakhaee-Pour and Bryant (2014) [38]. Samples with strong hysteresis tended to have a larger proportion of clay-related pores (intragranular pores) compared to samples with weak hysteresis.

5.2 Diagenetic facies

5.2.1 Characterization

Based on the microscopic imaging of detrital composition, texture, diagenetic mineral, and pore structure characteristics, five diagenetic facies were identified. The names of each diagenetic facies in a form of interstitial minerals plus pore type was as follows: (a) pore-lining chlorite intergranular pores dominated facies, (b) pore-filling chlorite intermediate pores dominated facies, (c) illite intragranular pores dominated facies, (d) authigenic quartz intragranular pores dominated facies, and (e) carbonate tight facies. Typical petrographic and SEM observations of each diagenetic facies were shown in Figure 12. For different diagenetic facies, the type and the degree of diagenetic minerals and the pore structure varied significantly.

Pore-lining chlorite intergranular pores dominated facies (PLCIEF) referred to the sandstones where the pore-lining chlorite was abundant and could easily be distinguished by SEM and the dark lines around the grains by thin section micrographs (Figure 12(a and b)). The pore-lining chlorite held a large proportion of the clay minerals, which were mainly platy like and developed on the surface of the grains. This abundance of clay minerals in PLCIEF determined the high degree of intergranular pores, as this kind of chlorite only occupied the small part of the intergranular pores and could resist compaction as well as illite and/or authigenic quartz cementation [56]. The high thin section porosity also resulted in the absence of ductile grains, which transformed in the process of mechanical compaction. The pore system in PLCIEF was mainly intergranular dominant, and the capillary pressure showed the occurrence of partial percolations. The saturation increased from 0.58% to 41.51% over a small range of capillary pressure and low entry pressure ($P_d = 0.07$ MPa). The length of the plateau in this sample was the longest among all five kinds of diagenetic facies, and the capillary pressure exponential over the saturation occurred when

saturation was over 41.51%, which indicated that intergranular pores made up a significant proportion in total volumes of PLCIEF. The withdrawal of mercury was partly reversible until the mercury saturation reaches 63.53%, revealing that void space was dominated by intergranular pores with few connected treelike pores (Figure 12(c)).

Pore-filling chlorite intermediate pores dominated facies (PFCIEF) referred to the sandstone where pore-filling chlorite was rich. An increase in the ratio of the pore-filling chlorite to the pore-lining chlorite led to the decrease of the pore radius as the rosette-like chlorite remained in the middle of the pores (Figure 12(d and e)). In some cases, the clay minerals such as illite, which blocked the throats, could be observed and provided some intragranular pores at the same time. The increased mechanical compaction of ductile grains could explain the lower proportion of intergranular pores in PFCIEF compared to PLCIEF. The pore system in PFCIEF was mainly intermediate dominant, which had widespread intergranular voids accompanied with intragranular pores, while the connectivity became worse. The entry pressure (0.27 MPa) increased compared to PLCIEF, and the plateau-like trend is still visible (percolation occurs from 19.37% to 57.53%). The pressure exponential over the saturation existed from the mediate point to the endpoint, which was an indicator of intragranular pores. There exerted a strong hysteresis in PFCIEF ($S_r = 79.67\%$) compared to PLCIEF, and plenty of residual phase trapping occurred in the pores as the initial connected path of the mercury, which existed to the outside became narrow or even clogged due to the occurrence of pore-filling chlorite (Figure 12(f)).

Illite and mixed-layer illite/smectite were abundant in illite-intragranular pores dominated facies (IIAF). Samples of IIAF could be identified by hair or honeycomb-like illite and mixed-layer illite/smectite under an SEM (Figure 12(g)). The illite and mixed-layer illite/smectite were mainly present in the intergranular pores, sometimes perpendicular to the grain surfaces and locally bridging pores and throats, which might have reduced physical properties, especially permeability, significantly [57]. Samples of IIAF were generally abundant in intragranular pores, and the micro cracks inside the grain could have been created by compaction (mechanical and/or chemical) (Figure 12(h)), while the dissolved feldspar provided a source for kaolinite and could have conversed to illite and mixed-layer illite/smectite aggregate in late diagenesis [46]. The plateau-like trend was observed at a mercury saturation range of 8.59% to 33.29%, which also indicated that there were some intergranular pores remained connected (Figure 12(i)). The decrease of residual mercury saturation ($S_r = 77.21\%$) meant that the proportion of treelike pores (intragranular pores)

Figure 12: Micrographs and capillary pressure curves of representative samples from each diagenetic facies: (a) PLCIEF (thin section); (b) PLCIEF (SEM); (c) capillary pressure curves of PLCIEF; (d) PFCIEF (thin section); (e) PFCIEF (SEM); (f) capillary pressure curves of PLCIEF; (g) IIAF (thin section); (h) IIAF (SEM); (i) capillary pressure curves of IIAF; (j) AIAF (thin section); (k) AIAF (SEM); (l) capillary pressure curves of AIAF; (m) CTF (thin section); (n) CTF (SEM); (o) capillary pressure curves of CTF. PLCh, pore-lining chlorite; PFCb, pore-filling chlorite; II, illite; I/S, mixed-layer illite/smectite; MC, micro crack; QA, authigenic quartz; Fc, ferrocaltite; An, ankerite; the gray box in capillary pressure curves indicates partial percolation.

increased because of illite and mixed-layer illite/smectite as well.

Authigenic quartz-intragranular pores dominated facies (AIAF) could be distinguished by the extensive quartz cements in thin section micrographs (Figure 12(j)). Quartz cementation along with clay minerals and carbonate had good control on the porosity and permeability. The authigenic quartz occurred as overgrowths adjacent to detrital quartz grains, and the thin dashed line was the boundary of detrital quartz and authigenic quartz cements (Figure 12(k)). The quartz cements were also engulfed by chlorite and illite, and the thickness of quartz cements appeared to be similar (Figures 6(c, d) and 12(j)). No plateau-like trend in AIAF on plotting capillary pressure on a logarithmic scale indicated that there were very few intergranular pores and stacks of intragranular pores (Figure 12(l)). The mercury saturation decreased notably when the capillary pressure decreased from 200 to 0 MPa ($S_r = 63.68\%$), which meant that the treelike pores make up the largest proportion among all five diagenetic facies due to the authigenic quartz cements and other clay minerals.

Carbonate tight facies (CTF) could be recognized by the broad red ferrocalcite and blue ankerite (Figure 12(m)). Carbonate was the dominant mineral within these diagenetic facies. The mechanical compaction was limited due to the ferrocalcite and ankerite cementation, while the porosity was less than 8.0%. Authigenic quartz and clay minerals were seldom observed in CTF as the carbonate cements limited the occurrence of other authigenic minerals (Figure 12(n)) [58–60]. No percolation occurred in CTF, and some pores were not invaded at a relatively high pressure because access to these was only by way of narrower throats with radius less than 3.6 nm (equivalent to the capillary pressure of 200 MPa according to the Washburn equation (1921)). The withdrawal curve was a partly reversible process, while the residual mercury saturation ($S_r = 75.00\%$) in CTF was larger than those in AIAF ($S_r = 63.68\%$) and close to those in PLCIEF (77.01%), indicating that intergranular pores among the carbonate aggregates dominate the pore system in CTF (Figure 12(o)).

5.2.2 Plane distribution

Based on the sand body distribution (Figure 1b) and experimental results, plane distribution of diagenetic facies was identified (Figure 13). Due to the provenance direction in the research area (mainly from the northeast, partly from the southwest, and few from the northwest), the plane distribution of different diagenetic facies was along the same direction. PLCIEFs were mainly distributed in the east

Figure 13: Plane distributions of diagenetic facies in the research area.

part of the research area, followed by the intersection of two provenance (mainly northeast-southwest and partly northeast-northwest). PFCIEF was the most widely distributed diagenetic facies, primarily distributed in the north part of the research area, while AIAF play a dominate role in the southwest part of the region. The distribution of IIAF has no significant principles, but mainly adjacent to PLCIEF and PFCIEF. CTF was mainly in the edge of interdistributary bay, indicating the thin sand body.

5.3 Timing of diagenetic processes

5.3.1 Eodiagenesis

Eodiagenesis was dominated by the impacts of the original depositional interstitial waters [61]. Initial mechanical compaction in the shallow layer of the Chang-6 formation in the Ordos Basin played an important role in deteriorating the porosity, which was mediated by progressive burial. Some microcrystalline calcite precipitated at a similar time as the feldspar dissolution from petrographic evidence, which displayed

evidence of partial dissolution, and the microcrystalline calcite were post-dated by later poikilotopic calcite. Detrital grains dissolution resulted in the kaolinization of framework grains. The chlorite that occurred as well-developed needle shaped, perpendicular to the grain surface, was another typical eogenetic cement. The early stage of quartz overgrowth occurred before the deformation of ductile grains (Figure 14).

5.3.2 Mesodiagenesis

Progressive burial reduced porosity of the Chang-6 sandstones continually, and the concave-convex quartz contacts appeared because of pressure dissolution. Chlorite cement occurred as a relatively minor phase in mesodiagenesis, and the kaolinite to illite and mixed-layer illite/smectite reaction from about 120°C to 130°C led to trace amounts of kaolinite in the Chang-6 sandstones [46]. The increasing burial depth and the temperature led to the generation of organic acids and carbon dioxide by thermal maturation in the source rocks. The dissolution of detrital grain resulted in enhancement of dissolved pores. Ferrocalcite and ankerite precipitated at the late stage of mesodiagenesis, which had slightly higher temperature ranging from 110°C to 165°C [57], and the mode was higher than quartz cements, indicating that they were post-dated quartz cements (Figure 14).

5.4 Diagenetic and pore structure control on reservoir quality

Provenance, depositional environment, diagenetic alteration, and pore structures had a high correlation with

reservoir quality [16,47], defined by porosity and permeability. Since there were few changes in grain size, sorting the provenance and depositional environment was insignificant for reservoir quality. Thus, diagenesis and pore structures were the main controlling factors.

Compaction and cementation were the main types of diagenesis that played vital roles in changing original porosities in the study area [2]. The compactional porosity loss (COPL) and cementational porosity loss (CEPL) were calculated by Lundegard (1992) [62]. A plot of intergranular volume versus cements showed that porosity decrease was chiefly controlled by compaction and cementation. Mechanical compaction and cementation accounted for 1.52–100.00% (av. 69.66%) and 0.00–98.48% (av. 30.34%), respectively, which meant that mechanical compaction was more crucial than cementation in destroying porosity (Figure 15). Figure 16(a–d) showed that carbonate and clay minerals controlled the reservoir quality to some extent, and the carbonate and pore-filling clay minerals tend to sit in pores and throat and reduced porosity and permeability. However, only samples with relatively low content of carbonate or low carbonate and pore-filling clay minerals content had relatively high porosity and permeability.

The maximum pore radius and medium pore radius had high correlation with reservoir quality, especially permeability (Figure 17(a–d)). Maximum pore radius had a relatively good relationship with porosity when compared with medium pore radius, indicating that the porosity was mainly controlled by intergranular pores and had relatively large diameters (Figure 17(a and c)). The relationship between medium pore radius and permeability was relatively good (Figure 17(d)), indicating that intragranular pores that had smaller size, played a more important role in increasing permeability compared to intergranular pores. The amount of single

Figure 14: Paragenetic sequence of the diagenetic minerals in the research area. The width represents the occurring rate of minerals, line means trace amount of mineral occurs, and length indicates relative time.

Figure 15: (a) Plot of CEPL vs COPL and (b) plot of cements volume vs intergranular volume for the Chang-6 sandstones.

cement and isolated pore radius parameter showed a weak correlation with the reservoir quality (R^2 lower than 0.3), indicating that the reservoir quality prediction models with various diagenetic facies need to be reconstructed to provide insights into accurately evaluating the reservoir quality.

5.5 Reservoir quality prediction models with various diagenetic facies

For PLCIEF, the typical eogenetic diagenesis was mechanical compaction and grain dissolution, and the

initial porosity was about 39.55%. The abundance of detrital quartz and other rigid rock fragments limited the mechanical compaction to some extent (porosity after compaction: 22.66%), and the acids generated by thermal maturation of organic matters in the source rocks and kaolinization of feldspars in eodiagenesis caused the dissolution of feldspar during deep burial in mesodiagenesis (Figure 12(a and b)), while the dissolved pores provided some scope for porosity improvement (+2.31%). The chlorite in the study area was mainly pore-lining chlorite and related to the abundance of rock fragments and biotite, which were rich in Fe^{2+} and Mg^{2+} ions [63]. The conversion of smectite into chlorite also persisted during the mesodiagenesis because of high

Figure 16: Reservoir quality data (core analysis physical properties) from the Chang-6 sandstones: (a) porosity vs quantity of carbonate, (b) permeability vs quantity of carbonate, (c) porosity vs quantity of carbonate plus pore-filling clay minerals, and (d) permeability vs quantity of carbonate plus pore-filling clay minerals.

Figure 17: Reservoir quality data (core analysis physical properties) from the Chang-6 sandstones: (a) porosity vs maximum radius, (b) permeability vs maximum radius, (c) porosity vs medium radius, and (d) permeability vs medium radius.

Fe^{2+} and Mg^{2+} ions [63]. The occurrence of pore-lining chlorite also played a vital role in mechanical compaction resistance, because of the limited compressibility of void volumes in PLCIEF (porosity after cementation: 13.66%). The intergranular pores were the major pore type in PLCIEF (Figure 12(c)), and the pores throat connectivity of PLCIEF was the best among all five kinds of diagenetic facies with the best reservoir quality (current porosity for typical sample: 15.97%) (Figures 14, 18 and 19).

For the samples of PFCIEF, the initial porosity was estimated to be 39.61%. The intensity of mechanical compaction occurred after the deposition was larger than that in PLCIEF because of relatively low contents of rigid rock fragments and detrital quartz, and the compaction of biotite and mica into pseudomatrix resulted in a significant reduction of porosity (porosity after compaction: 17.65%). Unlike the PLCIEF, the pore-filling chlorite in late-stage mesodiagenesis resulted in a progressive decrease in porosity and caused relatively strong hysteresis of the MIP data since the clay-related pores among chlorite were connected like intergranular pores (porosity after cementation: 9.65%) (Figure 12(d–f)). Dissolution increased the porosity to some extent (+4.82%). The reservoir quality of PFCIEF ranked second among the five diagenetic facies (current porosity for typical sample: 14.47%) (Figures 14, 18 and 19).

Illite and mixed-layer illite/smectite were the most widely distributed clay minerals in IIAF and occurred as pore-filling cements (Figure 12(g and h)). Those clay minerals precipitated fast in the stage of eodiagenesis

(porosity after cementation: 10.06%), and the K^+ for transformation of smectite into illite and illite smectite mixed layer in the stage of mesodiagenesis was derived from the feldspar dissolution (enhanced porosity: 0.57%). The porosity loss caused by compaction was small due to the high proportion of quartz and feldspar, and the ductile fragments were lesser (porosity after compaction: 27.96%). The illitization of kaolinite persisted during the mesodiagenesis caused the absence of kaolinite. The hysteresis of MIP became weak as the number of treelike pores (intragranular pores related to the illite and mixed-layer illite/smectite) increased (Figure 12(i)). Cementation by illite and mixed-layer illite/smectite resulted in a reduction of total porosity (current porosity for typical sample: 10.63%) (Figures 14, 18 and 19).

The initial porosity of AIAF was estimated as 39.30%. In eodiagenesis, the reduction of porosity was mainly attributed to mechanical compaction (porosity after compaction: 16.36%), quartz cements significantly reduced the reservoir porosity (porosity after cementation: 3.36%), and the deep burial as well as high temperature lead to the development of quartz cements in mesodiagenesis (Lai *et al.*, 2016). The concave–convex grain contacted in thin section micrographs and the authigenic quartz cements in SEM provided direct evidence of quartz cementation (Figure 12(j and k)). As mentioned earlier, the smectite-to-illite reaction and chemical compaction were the main sources of silica, which precipitated by quartz cements ranging from 60°C to 120°C during deep-burial mesodiagenesis (Figure 9). The quartz cements were the main cause of primary

Figure 18: Burial, temperature diagenetic history, and porosity evolution trend of the Chang-6 sandstone reservoirs. The proportion below the dot is the remained porosity after certain diagenesis. Φ_1 , initial porosity; Φ_2 , porosity loss caused by compaction; Φ_{3-e} , porosity loss caused by eodiagenetic cementation; Φ_4 , porosity increase caused by dissolution; Φ_{3-m} , porosity loss caused by mesodiagenetic cementation.

porosity reduction and always filled the intergranular pores. The pores among the quartz cements were treelike, which resulted in the weakest mercury

intrusion-withdrawal hysteresis among all five diagenetic facies (Figure 10(l)) for which the current porosity was 10.09% (Figures 14, 18 and 19).

Figure 19: Diagenetic evolution for different diagenetic facies for the Chang-6 sandstones.

For CTF, the formation of carbonate cements persisted from eodiagenesis to mesodiagenesis. The porosity decreased mainly due to compaction during eodiagenesis (Figure 12(m and n)), while some microcrystalline nonferro calcite and dolomite also played a vital role in this stage. The eodiagenetic carbonate cements caused less compaction as nonferro calcite and dolomite formed prior to extensive compaction [64], and the lack of quartz cements in CTF indicate that the nonferro calcite and dolomite predated the quartz cements. The compaction was limited in mesodiagenesis, while the ferrocalcite and ankerite precipitated during the late-stage mesodiagenesis because of the Fe^{2+} supply, which was caused by feldspars dissolution. The illitization of kaolinite filled the volumes and caused very low porosity (porosity after cementation: 1.54%). The lowest mercury saturation in CTF also provided the evidence of low porosity (Figure 10(o)). The reservoir quality was the worst when the current porosity was equal to 6.17% (Figures 14, 18 and 19).

6 Conclusions

1. The sandstones of Chang-6 were mostly lithic arkose, arkose, and feldspar litharenites with poor to well sorting and subangular roundness. The physical properties were quite poor with low porosity and permeability.
2. Mechanical and chemical compaction, quartz cementation, carbonate alteration, clay minerals cementation, and feldspar dissolution were the main diagenesis in Chang-6 sandstones.
3. Intergranular and intragranular pores were the main pore types in Chang-6 sandstones, which are mainly related to residual volume among detrital grains and clay mineral aggregate, respectively. The conventional network model could interpret the percolation in intergranular pores, while the treelike model was able to assess the intragranular pores.
4. According to the microscopic petrographic observations and capillary pressure curves, five major diagenetic facies were defined, namely, pore-lining chlorite intergranular pores dominated sandstones, pore-filling chlorite intermediate pores dominated sandstones, illite intragranular pores dominated sandstones, authigenic quartz intragranular pores dominated sandstones, and carbonate tight sandstones.
5. Smectite-to-illite reaction and chemical compaction were the main sources of internal silica for quartz cementation. Apart from the primary lacustrine

carbonates, which was one of the main source of carbonate cements, carbon and other ions related to carbonate cementation could have been expelled from source rocks to the adjacent sandstones.

6. The loss of porosity was greater due to compaction compared to cementation. The relatively low contents of carbonate and pore-filling cements, as well as relatively high maximum and medium pore radius, played vital roles in determining the reservoir quality.
7. Porosity evolution and diagenetic pathways of different diagenetic facies were reconstructed based on diagenetic alterations and pore structure features. The characteristics of the paramount diagenesis and pore structure are the result of the reservoir quality assessment.

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Appendix

Figure A1: The proportion of different components.

Table A1: The proportion of different components

Yellow debris		Orange debris		Grey debris		Dark debris		Total area
No.	Area	No.	Area	No.	Area	No.	Area	
1	9.51	1	10.74	1	41.84	1	5.59	3258.82
2	17.55	2	2.16	2	26.65	2	8.44	
3	8.14	3	2.5	3	10.18	3	11.02	Porosity
4	3.47	4	4.09	4	18.71	4	16.38	39.09%
5	1.83	5	5.19	5	64.17	5	44.63	
6	6.99	6	5.98	6	5.18	6	49.36	
7	25.99	7	15.01	7	6.55	7	16.8	
8	34.98	Subtotal	45.67	8	19	8	18.97	
9	54.46			9	51.65	9	6.4	
10	5.17			10	17.01	10	42.04	
11	6.89			11	47.12	11	8.84	
12	84.19			12	38.9	12	7.44	
13	41.12			13	21.22	13	13.89	
14	62.49			14	64.28	14	1.75	
15	74.59			15	42.86	Subtotal	251.55	
16	17.7			16	6.39			
17	4.16			17	27.13			
18	17.65			18	25.42			
Subtotal	476.88			19	66.63			
				20	16.11			
				21	57.78			
				22	30.57			
				23	53.86			
				24	48.94			
				25	9.79			
				26	8.45			
				27	66.03			
				28	3.61			
				29	68.28			
				30	19.7			
				31	57.49			
				32	20.49			
				33	22.76			
				34	45.34			
				35	19.2			
				36	6.29			
				37	21.83			
				38	33.23			
				Subtotal	1210.64			