

## Article

# Diagenetic Evolution and Its Impact on Reservoir Quality of Tight Sandstones: A Case Study of the Triassic Chang-7 Member, Ordos Basin, Northwest China

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**Abstract:** The Upper Triassic Chang-7 Member of the Ordos Basin contains typical tight sandstone reservoirs. Reservoir quality is affected by diagenesis, which is a critical factor in tight oil exploration. In this study, the Chang-7 Member tight sandstones were studied by a variety of experimental methods, including thin sections, scanning electron microscopy (SEM), and X-ray diffraction (XRD), to determine the reservoir characteristics and diagenesis and discuss their influences on the reservoir quality. The Chang-7 Member sandstones are mainly lithic arkose and feldspathic litharenite with an average porosity and permeability of 7.17% and 0.13 mD, respectively. The pore type is mainly primary intergranular pores, and the secondary pores are feldspar dissolved pores, which are relatively developed, with pore radii of 2–20  $\mu\text{m}$ . Diagenesis of Chang-7 Member tight reservoirs mainly includes compaction, quartz cementation, carbonate cementation, clay mineral cementation, and dissolution. The diagenetic stage develops into Mesodiagenesis A. The average porosity loss from compaction and cementation of sandstone in the Chang-7 Member is 15.93% and 18.67%, respectively. With the increase in burial depth, the porosity and permeability of the reservoir gradually decrease. In mesodiagenesis, the authigenic illite and carbonate cementation compacts the reservoir. The acid fluid carried by the two stages of oil and gas filling during diagenesis dissolved feldspar and carbonate cement, which plays a certain role in transforming the tight reservoir.

**Keywords:** tight sandstone; reservoir quality; diagenesis; Chang-7 Member; Ordos Basin

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## 1. Introduction

With the reduction of conventional resources and the breakthrough of development technology, the tight reservoir is the focus of unconventional oil and gas exploration and development in the world [1–3]. Tight oil reservoirs are generally fine-grained sediments, which experience complex diagenesis, resulting in the gradual densification of the reservoir in the process of burial and thermal evolution [4–8]. Therefore, they usually have a poor reservoir quality, small pore throat radius, low permeability, large diagenetic differences, and strong heterogeneities [9–11].

Porosity and permeability are important evaluation parameters to assess reservoir quality [12,13]. The porosity and permeability of tight reservoirs are mainly controlled by the sedimentary environment and diagenesis; the diagenesis after burial, in particular, is an important factor affecting reservoir quality. It includes physical and chemical changes that vary with depth, temperature, pressure, and fluid composition after deposition [12,14]. Diagenesis affecting reservoir quality mainly includes compaction, cementation, and dissolution [15–17]. Compaction and cementation often have the effect of pore reduction, resulting in the reduction in reservoir quality. On the other hand, dissolution can form

secondary pores with a pore-increasing effect, which leads to the improvement in reservoir quality.

China's tight oil resources are abundant and widely distributed and have become an important source of increasing oil and gas reserves and production [7,11,18]. The Ordos Basin is the basin with China's most abundant tight oil resources. The enrichment layer is located in the Chang-7 Member of the Triassic Yanchang Formation. The Chang-7 Member is a typical lacustrine tight sandstone reservoir with a complex and changeable sedimentary environment and strong diagenesis, resulting in a relatively dense reservoir and strong microheterogeneity. Although many publications have published the results and understanding of tight sandstone, the formation mechanism of tight sandstone remains to be explored [19–27]. Previous studies have shown that the main effects of diagenesis on the quality of the sandstone reservoirs in the Chang-7 Member are as follows: (1) compaction is the most important factor in reducing the porosity of a tight reservoir, and (2) the raw materials of carbonate cementation and quartz overgrowth in sandstone come from feldspar and adjacent mudstone [19–27]. However, the quantitative analysis of reservoir porosity and permeability is less for diagenesis, especially the cementation of different minerals.

The present research provides different insights into the above questions. It is considered that the effect of cementation on reservoir porosity and permeability is more important than compaction. In this study, tight sandstone samples from the Chang-7 Member of the Ordos Basin were examined by various methods to (1) clarify the reservoir properties and diagenesis of tight sandstone reservoirs, (2) evaluate the impacts of different diagenetic processes on the reservoir, and (3) establish the diagenetic evolution model. The purpose of this article is to provide a theoretical basis and practical guidance for effective exploration and development of tight sandstone.

## 2. Geological Setting

The Ordos Basin is a multicycle cratonic basin in Northern China, covering an area of 320,000 km<sup>2</sup> [28–30] (Figure 1). The basin can be divided into six first-order structural units: the Yimeng uplift in the north, the Weibei uplift in the south, the Jinxi flexure fold belt in the east, the Yishan slope in the center, the Tianhuan Syncline in the west, and a thrust belt in the west [29–32] (Figure 1b).

The basin was lacustrine during the Late Triassic, and Late Triassic was an important period in the history of oil genesis in the Ordos Basin [29–31]. The climate gradually changed from dry to humid, and the lake basin experienced an initial subsidence, expansion, shrinkage, and subsequent extinction [29–31]. The 1000–1500 m thick Yanchang Formation is a set of terrigenous clastic rocks, mainly alluvial fan, fluvial, deltaic, and lacustrine, in different sedimentary units [29]. The Yanchang Formation can be divided into ten subunits based on sedimentary cycles, named Chang-10 to Chang-1 from bottom to top, which record the complete development of a lake: initial formation and development stage (Chang-10 to Chang-8), peaking stage (Chang-7 to Chang-4+5), and declining stage (Chang-3 to Chang-1) [28–32] (Figure 1).

The Chang-7 Member can be subdivided into three submembers, named Chang-7<sub>3</sub>, Chang-7<sub>2</sub>, and Chang-7<sub>1</sub>, from bottom to top [29,30]. During the deposition of the Chang-7 Member, the lake expanded significantly, forming semi-deep and deep lake conditions. A large number of organic-rich sediments are considered as the target of high-quality hydrocarbon source and tight oil [33]. This provided the basis for the low and ultra-low permeability of the Yanchang Formation and the large-scale distribution of tight oil reservoirs within the Ordos Basin [29–31].

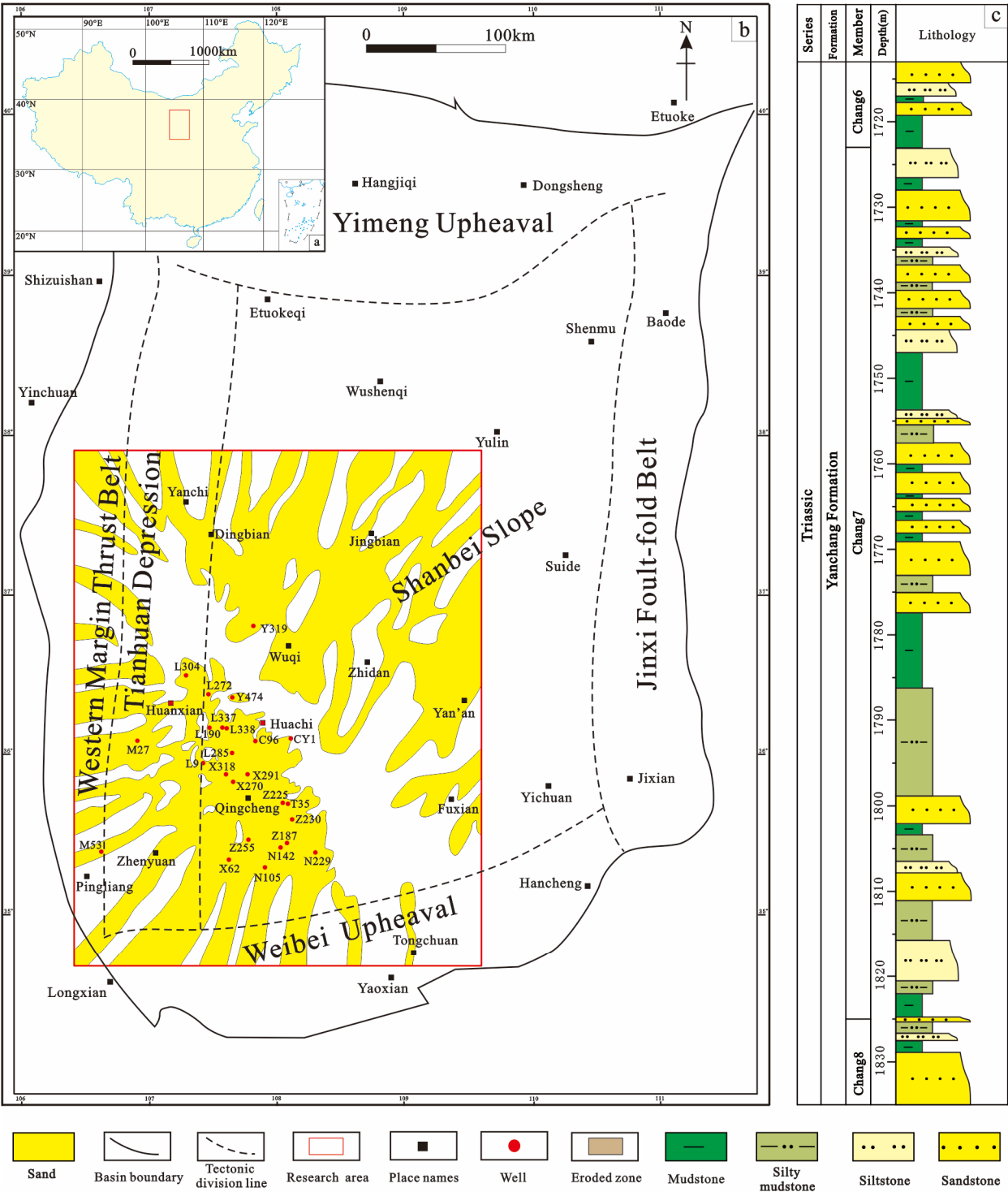


**Figure 1.** (a) Location of the Ordos Basin, China. (b) The geological background of the Ordos Basin, the study area, and the sampling well location; (c) lithologic profile of the Chang-7 Member strata [28–32].

**3. Materials and Methods**

All of the samples used in this study were taken from conventional cores from the Chang-7 Member of the Yanchang Formation, Ordos Basin. In addition, the Research Institute of Exploration and Development of PetroChina Changqing Oilfield Company provided a data set including sandstone composition data from 563 thin-section samples;

porosity and permeability testing results from 736 samples; and X-ray diffraction (XRD) data from 73 clay mineral samples.

### 3.1. Thin-Section Analysis

Eighty-five thin sections were impregnated with blue epoxy in a vacuum; they were stained with alizarin red-S and potassium ferricyanide, and carbonate minerals were identified according to Dickson [34]. The stain standards were 0.1 g alizarin red-S, 0.5 g potassium ferricyanide, and 0.2% HCL; samples were treated for about 1 min. They were examined using an Olympus optical microscope equipped with the Image-Pro Plus software.

### 3.2. Porosity and Permeability Analysis

The porosity and permeability of 215 sandstone samples were tested at room temperature and humidity. Porosity and permeability experiments were performed on  $25 \times 25$  mm columnar core plugs using a Micromeritics TriStar II 3020 helium porosity analyzer and Coretest Systems NDP-605 Ultra-low permeability meter, respectively.

### 3.3. Scanning Electron Microscopy

Scanning electron microscopy (SEM) was performed on 24 core samples using the Quanta 250 FEG in the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation at the Chengdu University of Technology to identify the morphology of minerals and pores.

### 3.4. X-ray Diffractometry

Whole-rock and clay fraction mineralogy were identified using X-ray diffraction (XRD) on 32 samples. The samples were first powdered using an agate mortar and pestle, and the sample preparation, analysis, and interpretation procedures used by Moore and Reynolds [35] and Hillier [36] were adopted. The characterization of whole-rock and clay fraction ( $<2 \mu\text{m}$ ) was performed using Japan Ultima IV X-ray diffractometer.

## 4. Results

### 4.1. Petrology

The lithology of the Chang-7 Member of the Triassic Yanchang Formation in the Ordos Basin is mainly fine-grained sandstone. According to Folk's classification scheme [37], the rock types of the Chang-7 Member are classified as lithic arkoses and feldspathic litharenites (Figure 2). Quartz (mostly monocrystalline) content ranges from 30.71% to 39.74%. Feldspar contents range from 21.32% to 24.40%. Lithic fragment contents range from 15.71% to 16.45%, comprising mainly metamorphic rock fragments ranging from 6.92% to 8.02%, sedimentary rock fragments ranging from 4.95% to 5.39%, and volcanic rock fragments ranging from 2.97% to 3.77%.

The cement is mainly clay mineral and carbonate cement, and the content of siliceous cement is low. The clay mineral is mainly illite, with a content of 8.89%. Carbonate cements are mainly dolomite, ankerite, and ferroan calcite.

Grain shape in the Chang-7 Member tight oil reservoir ranges from subangular to subrounded. Grains are moderately sorted and mineralogically immature with low textural maturity.

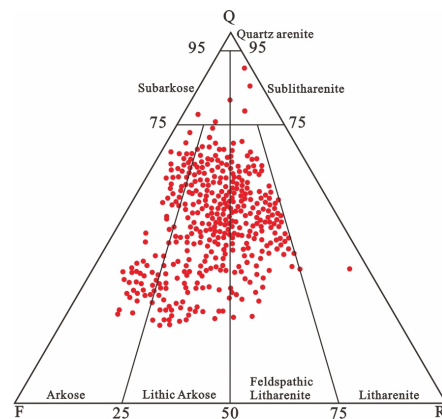


**Figure 2.** Ternary diagram showing the framework grain composition of the Chang-7 Member sandstones in the Ordos Basin [37].

#### 4.2. Reservoir Properties

##### (1) Porosity and permeability

Overall, the reservoir properties in the Chang-7 Member sandstones are quite poor (Figure 3). Porosity of core samples ranges from 0.5% to 12.3%, with an average of 7.17%. Permeability ranges from 0.02 mD to 1.82 mD, with an average of 0.13 mD. About 97.73% of the permeability values are lower than 1 mD, while the values greater than 1 mD are micro fractures.

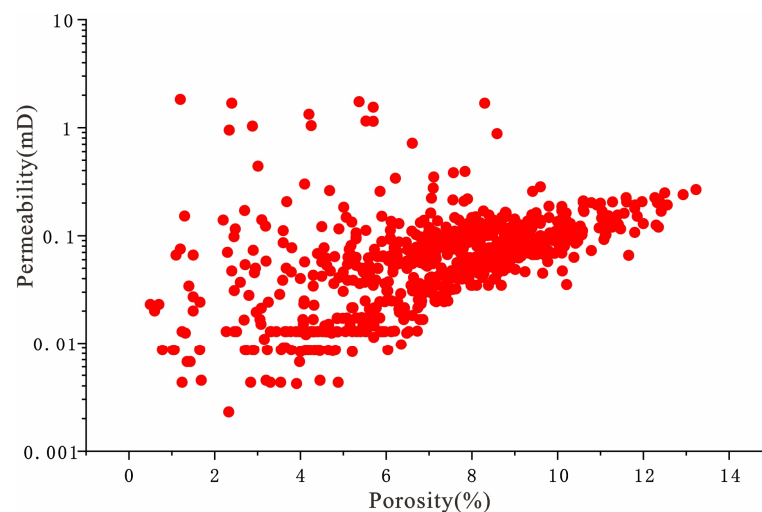


**Figure 3.** Core porosity vs. core permeability cross-plots for the Chang-7 Member sandstones in the Ordos Basin.

##### (2) Pore types and pore-throat characteristics

The pore types of the Chang-7 Member tight sandstones in the Ordos Basin are mainly intergranular pores, followed by feldspar-dissolved pores and rock-fragment-dissolved pores, and a small amount of intergranular dissolved pores and microfractures. Intergranular pores account for 57.57% of the total pores (Figure 4a); dissolved pores account for 40.48% of the total pores (Figure 4b–h), and other pores account for about 1.95% (Figure 4i). The pore throat scale of the sandstone reservoir in the Chang-7 Member is small. The pore radius is distributed 2–20  $\mu\text{m}$ , being mainly concentrated in the range of 2–8  $\mu\text{m}$ . The throat radius is distributed between 25 and 250 nm, being mainly concentrated in the range of 20–150 nm.

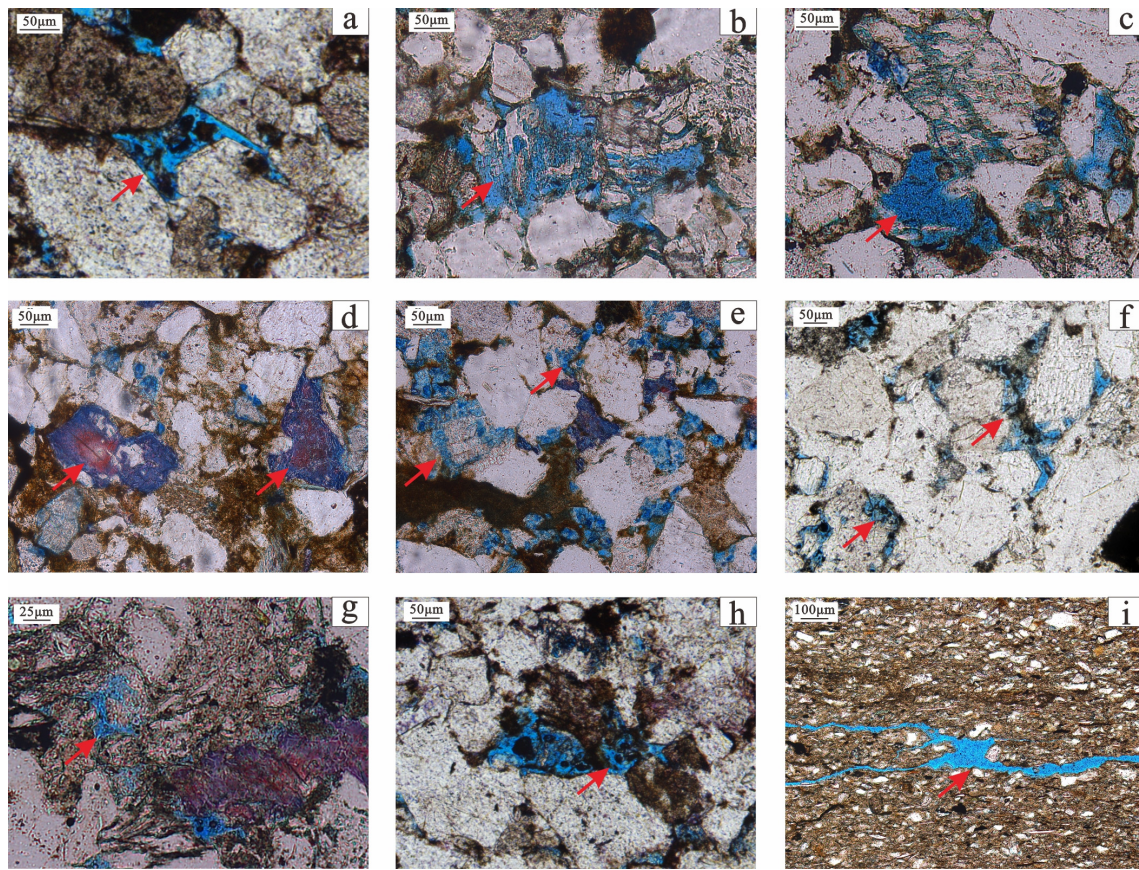


**Figure 4.** Pore types of the Chang-7 Member in Ordos Basin: (a) N229, 1710.14 m, intergranular pores; (b) L337, 2284.3 m, feldspar-dissolved pore; (c) Z255, 1748.4, melodic pore; (d) Z230, 1743.9 m, melodic pore; (e) L304, 2489.6 m, intergranular dissolved pore; (f) N229, 1710.14 m, intergranular dissolved pore; (g) M27, 2745 m, debris solution pore; (h) N229, 1737.98 m, debris solution pore; (i) L272, 2497.42 m, microcrack.

#### 4.3. Diagenetic Events and Characteristics

##### (1) Compaction

Compaction is an important reason for the decrease in reservoir quality in the early stage of diagenesis [12,38,39]. The lithology of the Chang-7 Member is mainly lithic arkose and feldspathic lithic sandstone, and the content of feldspar and plastic rock debris with weak compaction resistance is high.

Compaction changes the contact relationship between particles and the directional arrangement of debris particles (Figure 5a). The contact relationship changes from point contact to line contact and then to concave–convex contact (Figure 5b). Plastic components, such as plastic rock fragments and mica, are extruded and deformed (Figure 5c,e). Diagenetic minerals will rupture along the weak surface under pressure beyond their bearing capacity. Quartz is prone to wedge cracks (Figure 5d), and feldspar breaks along the cleavage plane or directly perpendicular to the cleavage plane (Figure 5f).

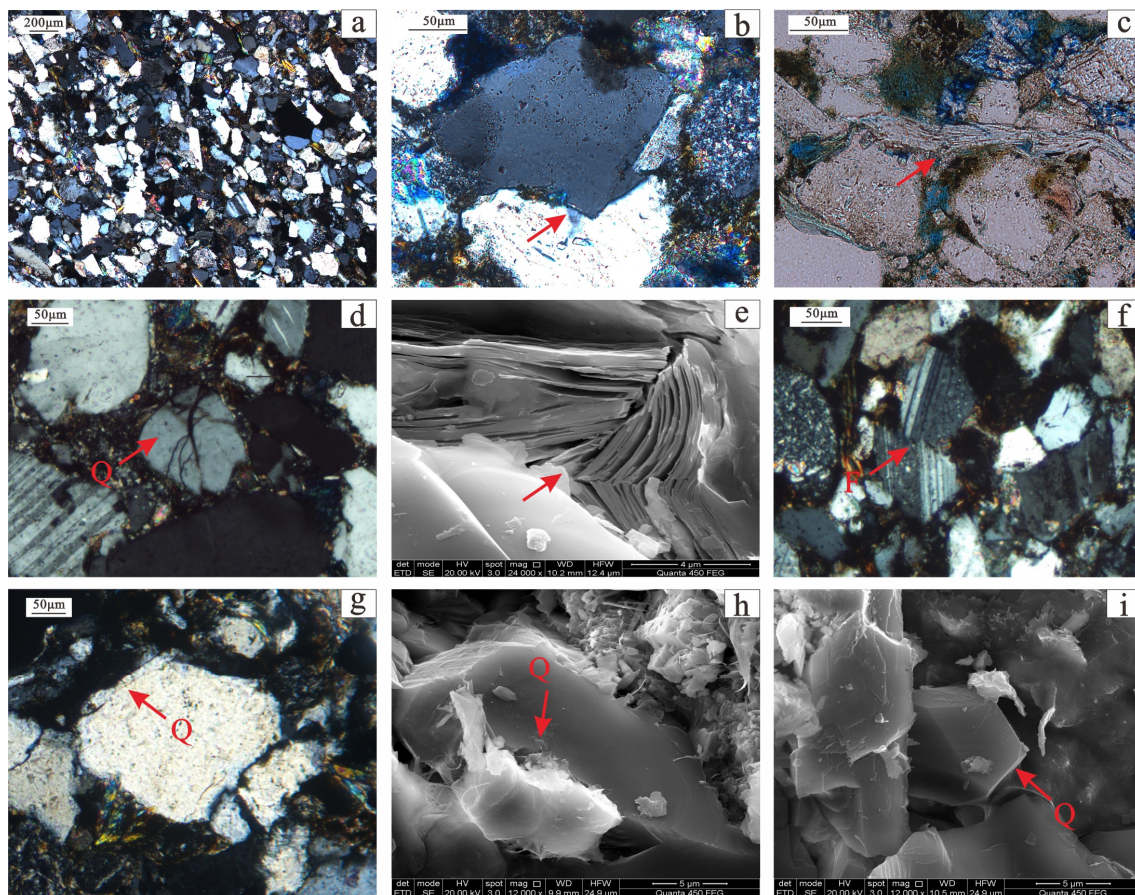


**Figure 5.** Compaction and quartz cementation of the Chang-7 Member in the Ordos Basin (Q: quartz; F: feldspar). (a) Z187, 1589.0 m, directional arrangement of clastic particles; (b) X270, 2042.97 m, concave–convex contact; (c) L190, 2259.24 m, mica-bending deformation; (d) N105, 1521.9 m, quartz particle breakage; (e) X318, 2020.8 m, mica fracture; (f) Y474, 2221.3 m, feldspar fracture; (g) N229, 1685.58 m, quartz overgrowth; (h) Z225, 1774.5 m, quartz overgrowth; (i) L337, 2284.3 m, authigenic-quartz-filled pores.

## (2) Cementation

Cementation is the most important type of chemical diagenesis in the tight sandstone reservoir of the Chang-7 Member in the Ordos Basin. Ions with different crystallization habits in diagenetic fluid form different types of authigenic diagenetic minerals under the comprehensive control of the nucleation mechanism and growth process to fill the reservoir space [40,41]. The cementation of the Chang-7 Member tight sandstone reservoir mainly includes siliceous cementation, carbonate cementation, and clay mineral cementation.

### (a) Siliceous cementation

Siliceous cementation is mainly characterized by the overgrowth of quartz and authigenic quartz. In the early stage of diagenesis, silica mainly comes from the precipitation of  $\text{SiO}_2$  in pore water, and the silica cement is mostly overgrown as quartz (Figure 5g,h). The siliceous cement in middle and late diagenesis mainly comes from the dissolution of feldspar and rock debris particles. Authigenic quartz is often filled in the pores in hexagonal biconical and crystal column shapes (Figure 5i).

### (b) Carbonate cementation

Carbonate cement is an authigenic mineral of high content in the tight sandstone reservoir of the Chang-7 Member, mainly including calcite, ferroan calcite, dolomite, and ankerite.

Calcite cement is mainly embedded cementation and pore-filling cementation. The pore-filling calcite crystal size is 10–200  $\mu\text{m}$  (Figure 6a). Under the scanning electron

microscope, the crystal form of calcite is a euhedral rhombohedron, and the cleavage on the surface of the calcite crystal is developed (Figure 6b). Some calcite cement can be seen to transition from red to purple from the center to the edge of the cement, reflecting the increase in iron ion content at the edge of calcite to form ferroan calcite [42] (Figure 6c).

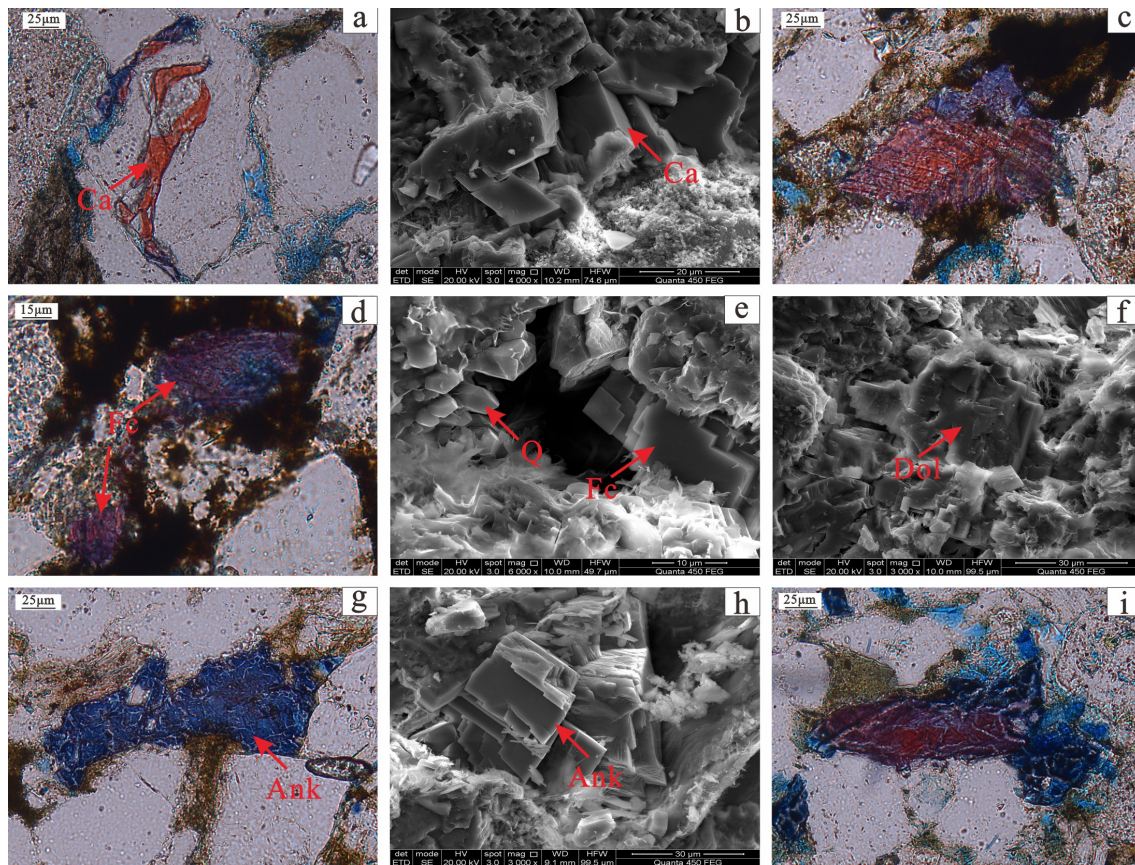


**Figure 6.** Carbonate cementation of the Chang-7 Member in the Ordos Basin (Q: quartz; Ca: calcite; Fc: ferroan calcite; Dol: dolomite; Ank: ankerite). (a) M27, 2745 m, calcite-filled pores; (b) Y474, 2221.3 m, inlaid cemented calcite; (c) X291, 2020.8 m, cementation of calcite and ferroan calcite; (d) L337, 2284.3 m, ferroan-calcite-filled pores; (e) Z230, 1743.9 m, ferroan-calcite-filled pores; (f) N142, 1687.8 m, dolomite; (g) X288, 2116.4 m, ankerite-filled pores; (h) L304, 2489.6 m, ankerite-filled pores; (i) L285, 2172.7 m, cementation of ferroan calcite and ankerite.

Ferroan calcite mainly fills pores (Figure 6d). Under the scanning electron microscope, the crystal size of ferroan calcite is about 10  $\mu\text{m}$ . The crystal shape is a self-shaped rhombohedron (Figure 6e), which is significantly smaller than the size of the calcite crystal.

Dolomite is mainly characterized by a discrete granular rhombohedron with a crystal size of 20–100  $\mu\text{m}$  (Figure 6f). It mainly grows in primary pores.

Ankerite is mainly characterized by a euhedral rhombohedron, and dispersed or aggregated ankerite can fill primary and secondary pores (Figure 6g). In addition, some irregular ankerite fills the residual space between early carbonate cement and clastic particles. The rhombohedral crystal form of ankerite is very apparent under a scanning electron microscope (Figure 6h).

Ferroan calcite, dolomite, and associated calcite often metasomatism with sedimentary particles. Metasomatism occurs along the edge or cleavage of particles. At the same time, metasomatism also occurs among the three minerals (Figure 6i).

#### (c) Clay mineral cementation

According to the XRD and SEM analyses, the clay minerals in the Chang-7 Member of the Ordos Basin are relatively developed, mainly including illite, illite-smectite (I/S),

kaolinite, chlorite, and their transition types, of which the content of illite is the highest, followed by I/S mixed layer minerals (Table 1).

**Table 1.** Petrophysical characteristics and XRD analysis data of tight sandstones in well C96 of the Chang-7 Member.

| Samples | Well | Depth (m) | Whole Rock Mineral (%) |       |       |      |       |      |       | Authigenic Clay Minerals (%) |       |      |       |        | Porosity (%) | Permeability (mD) |
|---------|------|-----------|------------------------|-------|-------|------|-------|------|-------|------------------------------|-------|------|-------|--------|--------------|-------------------|
|         |      |           | Q                      | Pla   | PF    | Ca   | Dol   | Sid  | Clay  | I                            | I/S   | K    | Ch    | I/S(S) |              |                   |
| 1       | C96  | 1964.82   | 38.75                  | 6.96  | 1.76  | /    | 16.14 | 2.18 | 32.86 | 54.43                        | 26.04 | 5.67 | 13.86 | 20     | 5.3          | 0.053             |
| 2       | C96  | 1965.59   | 46.28                  | 21.08 | 18.34 | 2.27 | 4.14  | 0.64 | 7.25  | 48.8                         | 25.53 | 6.11 | 19.57 | 15     | 8.4          | 0.107             |
| 3       | C96  | 1973.27   | 63.29                  | 13.45 | 4.32  | 2.12 | 4.59  | 0.87 | 11.35 | 48.97                        | 23.11 | 5.71 | 22.2  | 20     | 5.7          | 1.544             |
| 4       | C96  | 1981      | 55.45                  | 6.42  | 4.02  | 6.77 | 7.19  | /    | 12.16 | 49.22                        | 34.7  | /    | 16.08 | 20     | 0.6          | 0.02              |
| 5       | C96  | 1992.29   | 26.96                  | 10.48 | 2.82  | /    | 13.33 | 1.61 | 44.8  | 55.8                         | 27.51 | 4.24 | 12.45 | 20     | 7.4          | 0.094             |
| 6       | C96  | 1993.42   | 65.86                  | 17.75 | 3.06  | 0.67 | 2.75  | 0.76 | 9.15  | 54.45                        | 23.36 | /    | 22.18 | 20     | 9            | 0.136             |
| 7       | C96  | 1996.15   | 54.11                  | 13.64 | 5.69  | 1.97 | 5.18  | 2.01 | 17.4  | 55.75                        | 24.63 | 4.9  | 14.71 | 20     | 4.8          | 0.064             |
| 8       | C96  | 1997.39   | 41.87                  | 13.08 | 2.84  | 0.92 | 10.14 | 1.27 | 29.89 | 54.02                        | 28.68 | 4.12 | 13.18 | 20     | 7.6          | 0.09              |
| 9       | C96  | 1997.69   | 63.66                  | 16.13 | 6.18  | 1.48 | 2.13  | 1.03 | 9.41  | 53.26                        | 26.16 | 5.04 | 15.55 | 15     | 8.8          | 0.15              |
| 10      | C96  | 1998.64   | 63.37                  | 13.52 | 5.48  | 2.29 | 5.32  | 0.88 | 9.13  | 55.64                        | 22.72 | 7.02 | 14.62 | 15     | 9.3          | 0.136             |
| 11      | C96  | 2000.69   | 65.6                   | 13.39 | 5.64  | 1.18 | 2.92  | 0.9  | 10.37 | 55.8                         | 24.26 | /    | 19.95 | 15     | 8.8          | 0.163             |
| 12      | C96  | 2001.42   | 68.19                  | 12.21 | 4.14  | 1.57 | 3.22  | 0.94 | 9.73  | 59.97                        | 22.11 | /    | 17.93 | 15     | 9            | 0.142             |
| 13      | C96  | 2002.1    | 35.5                   | 14    | 3.07  | /    | 7.54  | 1.02 | 38.87 | 55.45                        | 27.45 | 3.19 | 13.91 | 20     | 6.6          | 0.066             |
| 14      | C96  | 2003.25   | 68.28                  | 14.19 | 2.68  | 1.26 | 2.97  | 1.09 | 9.53  | 61.42                        | 16.42 | /    | 22.15 | 15     | 10.6         | 0.174             |
| 15      | C96  | 2005.38   | 58.13                  | 22.06 | 3.54  | 0.58 | 5.01  | 0.67 | 10    | 61.52                        | 21.26 | 4.96 | 12.27 | 15     | 7.2          | 0.137             |
| 16      | C96  | 2006.6    | 66.51                  | 15.69 | 5.46  | 1.21 | 2.22  | 1.05 | 7.86  | 67.56                        | 7.16  | 6.17 | 19.11 | 15     | 10.1         | 0.128             |
| 17      | C96  | 2008.9    | 57.98                  | 17.43 | 10.76 | 1.03 | 2.09  | 0.66 | 10.05 | 55.86                        | 26.57 | /    | 17.57 | 15     | 6.7          | 0.102             |
| 18      | C96  | 2010.04   | 55.55                  | 18.68 | 7.81  | 1.12 | 4.7   | /    | 12.14 | 63.14                        | 22.55 | 3.68 | 10.62 | 15     | 3.2          | 0.058             |
| 19      | C96  | 2013.02   | 67.05                  | 13.18 | 4.33  | 1.04 | 2.44  | 0.77 | 11.19 | 53.4                         | 26.42 | 5.43 | 14.74 | 15     | 7.7          | 0.077             |
| 20      | C96  | 2014.58   | 56.99                  | 21.4  | 4.49  | 1.18 | 2.86  | 1.31 | 11.77 | 53.69                        | 28.24 | 4.51 | 13.57 | 20     | 6.8          | 0.081             |
| 21      | C96  | 2016.86   | 55.29                  | 14.17 | 19.75 | 1.13 | 2.3   | 0.76 | 6.6   | 59.68                        | 17.38 | 8.91 | 14.03 | 15     | 10.3         | 0.129             |
| 22      | C96  | 2018.3    | 63.92                  | 14.3  | 6.62  | 1.15 | 3.19  | 0.88 | 9.93  | 60.06                        | 16.09 | 6.29 | 17.55 | 20     | 7.7          | 0.139             |
| 23      | C96  | 2019.79   | 68.2                   | 13.09 | 4.16  | 1.23 | 2.47  | 0.94 | 9.92  | 60.84                        | 18.09 | 5.82 | 15.25 | 15     | 8.8          | 0.155             |
| 24      | C96  | 2021.34   | 61.74                  | 18.37 | 6.18  | 0.88 | 3.06  | 0.81 | 8.97  | 63.81                        | 15.97 | 5.8  | 14.41 | 15     | 8.1          | 0.139             |
| 25      | C96  | 2022.77   | 64.53                  | 10.78 | 8.55  | 3.15 | 2.33  | 1.18 | 9.48  | 61.1                         | 19.15 | /    | 19.75 | 20     | 7.1          | 0.081             |
| 26      | C96  | 2024.24   | 64.69                  | 10.3  | 5.8   | 1.16 | 5.41  | 1.34 | 11.3  | 61.06                        | 18.93 | 5    | 15.01 | 20     | 7            | 0.078             |
| 27      | C96  | 2026.85   | 57.92                  | 7.36  | 3.54  | 9.1  | 5.5   | /    | 10.25 | 62.8                         | 19.38 | /    | 17.83 | 15     | 4.3          | 0.034             |
| 28      | C96  | 2028.99   | 62.89                  | 16.24 | 2.94  | 1.14 | 5.09  | 1.45 | 10.25 | 65.18                        | 14.56 | 6.39 | 13.88 | 15     | 8.5          | 0.078             |
| 29      | C96  | 2033.45   | 56.09                  | 17.62 | 5.83  | 1.44 | 5.94  | 1.42 | 11.67 | 66.42                        | 16.12 | 7.25 | 10.21 | 20     | 7.6          | 0.075             |
| 30      | C96  | 2034.95   | 56.35                  | 15.25 | 3.66  | 0.88 | 5.15  | 1.5  | 17.21 | 59.1                         | 26.54 | 3.67 | 10.68 | 20     | 2.4          | 1.677             |
| 31      | C96  | 2039.32   | 60.63                  | 16.57 | 5.65  | 1.4  | 3.37  | 1.39 | 11    | 60.1                         | 21.99 | 4.14 | 13.77 | 20     | 5.6          | 0.048             |
| 32      | C96  | 2072.5    | 64.12                  | 15.71 | 5.87  | 0.81 | 3.86  | 0.73 | 8.89  | 67.08                        | 13.15 | /    | 19.77 | 20     | 8.7          | 0.084             |

Q: quartz; Pla: plagioclase; PF: potassium feldspar; Ca: calcite; Dol: dolomite; Sid: siderite; I: illite; I/S: mixed-layer illite/smectite; K: kaolinite; Ch: chlorite; “/” represents no data.

SEM observations showed that illite is mainly filamentous and honeycomb-shaped (Figure 7a) and distributed in intragranular pores (Figure 7b). I/S is mainly characterized by lamellar crystals (Figure 7c). With the transformation of smectite to illite, the edges of lamellar minerals curl, and the size of single crystals is between 5 and 10  $\mu\text{m}$ .

Kaolinite is generally a pseudo-hexagonal crystal, and the aggregates are mostly in the form of vermicular-stacked and booklet-shaped (Figure 7d,e). Single crystal size is 5–10  $\mu\text{m}$ . They are distributed in the intergranular primary pores and feldspar dissolution pores (Figure 7f).

Loose kaolinite aggregates can provide many intergranular micropores, expand pore space, and improve pore connectivity (Figure 7d). However, as the degree of diagenetic evolution deepens with the increase in burial depth, the edge of some kaolinite aggregates undergo illitization, forming filamentary illite (Figure 7e).

Chlorite rosettes cover the surface of detrital grains (mainly quartz and feldspar) and form grain coatings (Figure 7g–i). In the early stage of diagenesis, chlorite mostly covers the surface of clastic particles in a blade shape and needle shape (Figure 7g). In the middle stage of diagenesis, chlorite often fills the pores or adheres to the particle surface in leaf, petal, and pile ball shapes (Figure 7h).

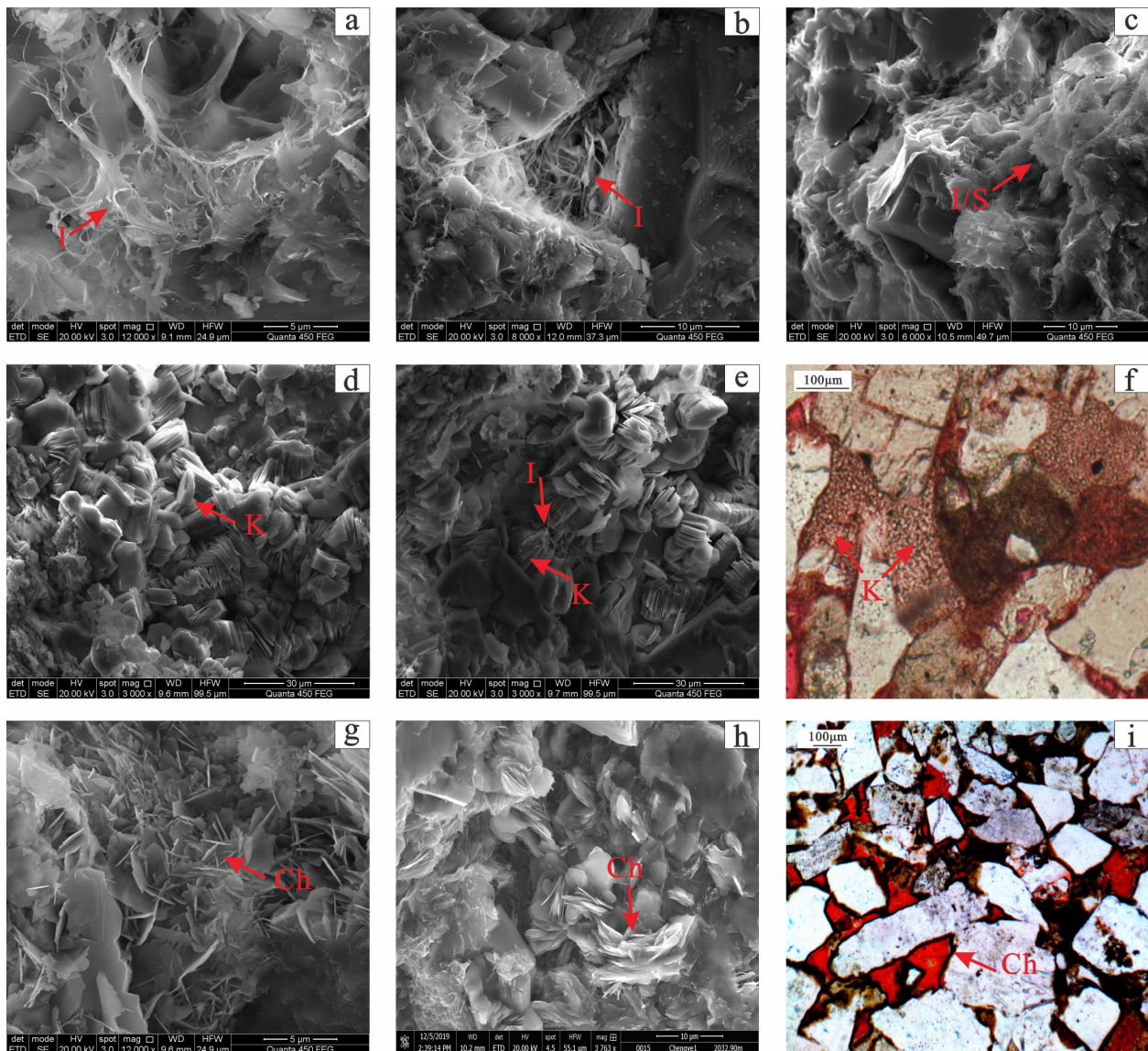


**Figure 7.** Clay mineral cementation of the Chang-7 Member in the Ordos Basin (I: illite; I/S: mixed-layer illite/smectite; K: kaolinite; Ch: chlorite). (a) L304, 2489.6 m, filamentous illite-filled pores; (b) L190, 2230.8 m, illite-filled pores; (c) N105, 1521.9 m, I/S; (d) M27, 2745 m, booklet kaolinite; (e) M27, 2745 m, booklet kaolinite and illitization; (f) M53, 2445.65 m, kaolinite fills the pores, and the clastic surface is covered with chlorite; (g) M27, 2745 m, blade chlorite; (h) CY1, 2032.9 m, autogenous chlorite-filled pores; (i) Y319, 2237.6 m, clastic surface is covered with chlorite.

### (3) Dissolution

The dissolution mainly show feldspar dissolution and carbonate cement dissolution in the study area.

The partial to total dissolution of feldspar is very common in the Chang-7 Member tight sandstone. Typical dissolution features include hollowed-out particle residues formed by partial dissolution of feldspar (Figure 8a). Molding pores are formed by the complete dissolution of feldspar particles (Figure 8b). Harbor-like dissolution pores form along the edge of feldspar (Figure 8c). Grid corrosion pores form along with feldspar cleavage fractures (Figure 8d).

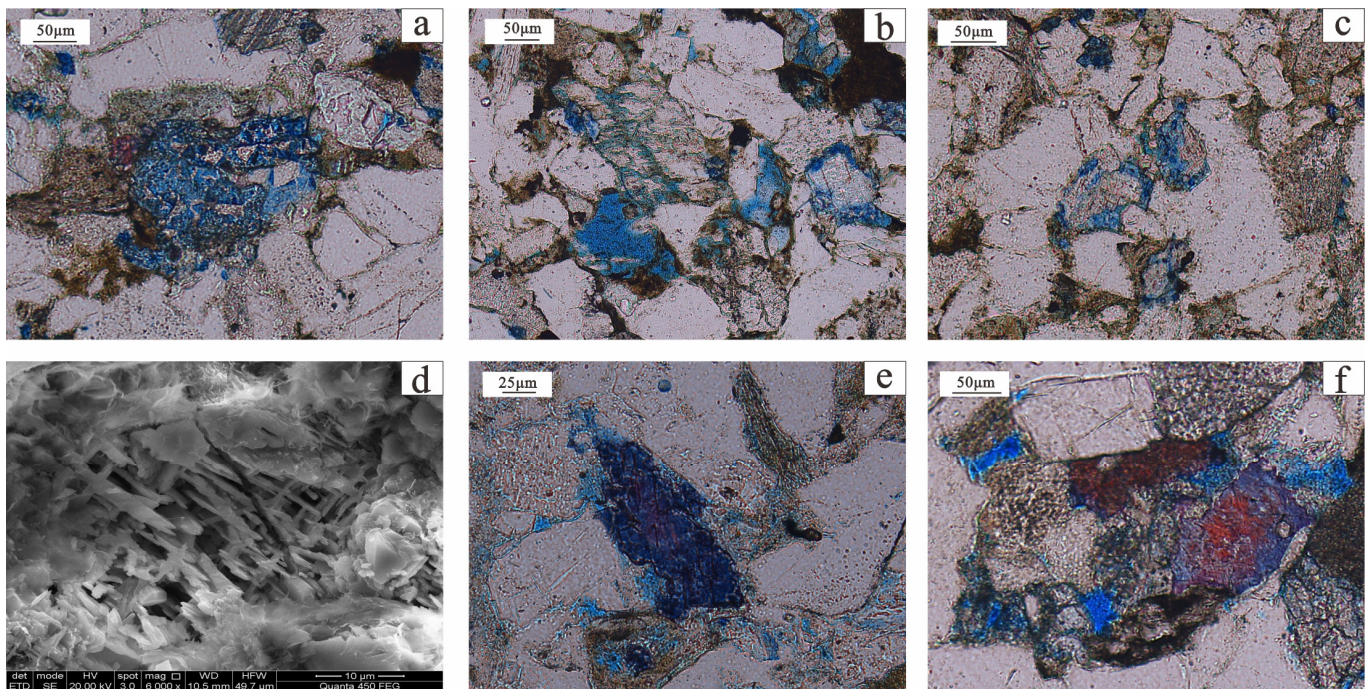


**Figure 8.** Dissolution of the Chang-7 Member in the Ordos Basin. (a) L190, 2267.8 m, hollowed-out particle residues formed by partial dissolution of feldspar; (b) Z255, 1748.4 m, melodic pores; (c) X62, 1838.82 m, harbor-like dissolution pores; (d) L338, 2329.3 m, grid corrosion pores; (e) Z255, 1774.5 m, ankerite boundary is corroded; (f) M27, 2745 m, calcite particle boundary is corroded.

The dissolution of carbonate cement exists in some reservoirs in the study area. The dissolution of calcite, ferroan calcite, and ankerite can be seen, which have significant dissolution petrographic characteristics (Figure 8e,f).

## 5. Discussion

### 5.1. Paragenetic Sequence of Diagenesis

The vitrinite reflectance ( $R_o$ ) values of the Chang-7 Member sandstones range from 0.7% to 1.07% [22,25,27]. XRD results of sandstone samples from the Chang-7 Member show that the mass fraction of smectite in I/S is between 15% to 20% (Table 1). According to the discrimination standard of I/S for diagenetic temperature [43] and fluid inclusion temperature, the maximum paleogeothermal temperature of the Chang-7 Member is 120 °C~140 °C.

Previous simulation results on the evolution of burial history and temperature history of the Chang-7 Member show that the stratum of the Chang-7 Member reached the maximum paleoburial depth of more than 2000 m in the Cretaceous period [22,25,27]. Furthermore, according to the division mark of a diagenetic stage of clastic rock (SY/T 5163-2010) [44], the sandstone reservoir of the Chang-7 Member is Mesodiagenesis A.

The diagenetic evolution sequence of sandstone was established by analyzing the relationship between the diagenetic minerals and diagenetic stages of the Chang-7 Member tight sandstones in the study area (Figure 9).

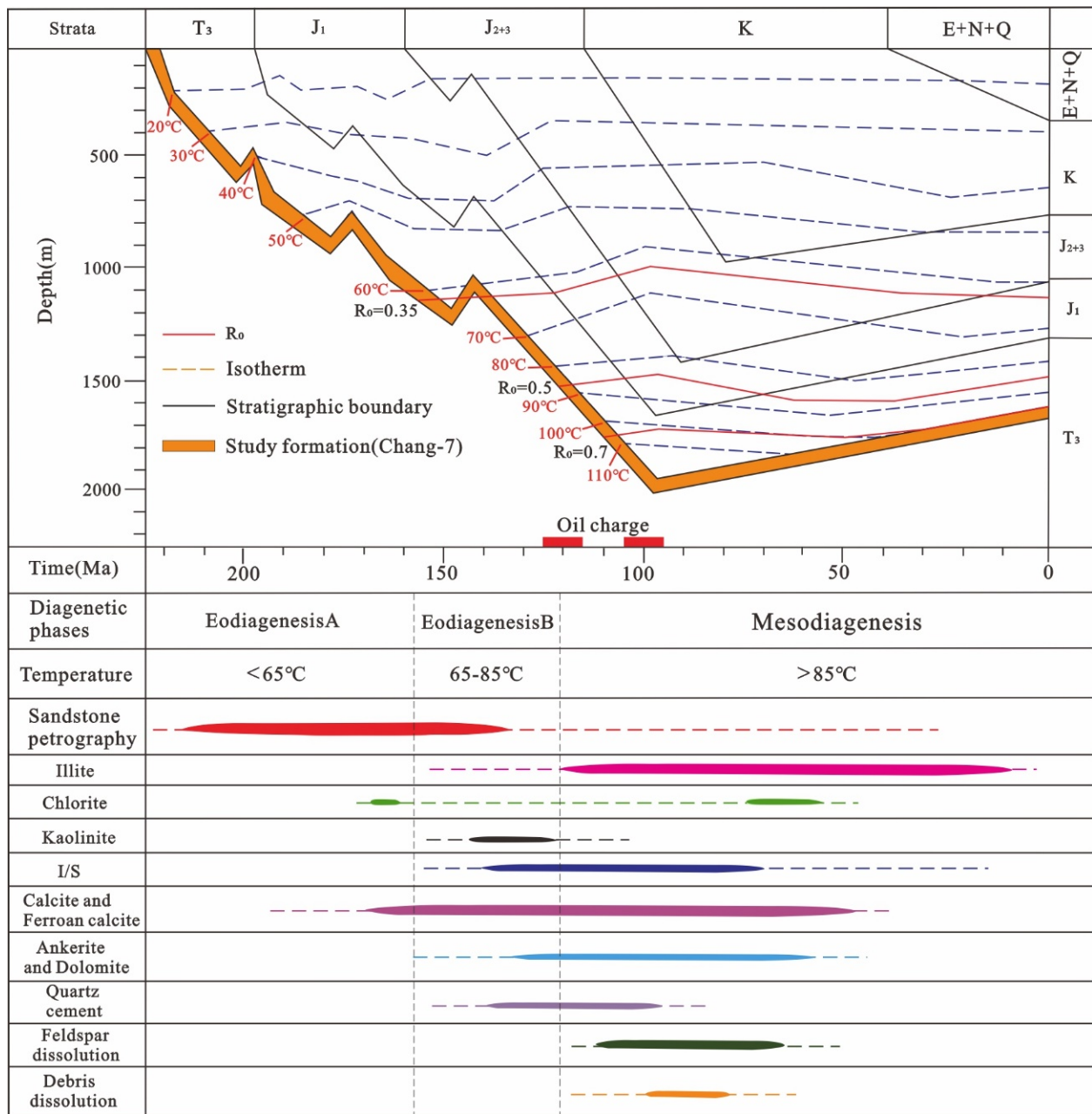


**Figure 9.** Burial, thermal, and the major diagenetic sequence of the Chang-7 Member in the Ordos Basin [22,25,27].

#### (1) Eodiagenesis

In Eodiagenesis A (normal temperature up to 65 °C, more than 159 Ma), the buried depth of the stratum is about 0–1100 m. Diagenesis is dominated by compaction, cementation, the directional arrangement of clastic particles (Figure 5a), and the deformation of plastic particles (Figure 5c). The chlorite film on the surface of quartz and feldspar particles slows down the compaction strength to a certain extent, and the leaching of atmospheric fresh water alters some debris particles, but the degree is low.

In Eodiagenesis B (65 °C to 85 °C, 159 Ma to 120 Ma), the buried depth of the stratum is about 1100–1500 m. Cementation becomes the main diagenesis. Smectite begins to transform into kaolinite and I/S. In clay mineral transformation, SiO<sub>2</sub> and Ca<sup>2+</sup> are released to form siliceous cement. At about 125 Ma, it experiences phase I oil injection, and the diagenetic fluid containing organic acid transforms the sandstone reservoir by dissolution.

Concurrently, organic acids inhibit early calcite cementation and can produce feldspar-dissolved pores.

## (2) Mesodiagenesis

In Mesodiagenesis (more than 85 °C, 120 Ma after), the Chang-7 Member experiences rapid settlement, with a burial depth of more than 1500 m, and the impact of compaction on the reservoir was reduced. With the gradual increase of paleogeothermal temperature, kaolinite and smectite are completely transformed into I/S and illite. At the same time,  $\text{SiO}_2$  and  $\text{Ca}^{2+}$  are released to participate in cementation to form quartz cement and carbonate cement to fill pores (Figure 5g,h and Figure 6).  $\text{Fe}^{2+}$  released from the transformation of clay minerals intrudes into carbonate cement to form iron-bearing carbonate cement. At about 105 Ma, it experiences phase II oil injection, and the invasion of organic acid locally transforms the reservoir quality, resulting in the dissolution of feldspar and carbonate cement and a large number of secondary solution pores (Figure 8).

Through the above research, the diagenetic sequence of the Chang-7 Member was determined to be as follows: compaction → chlorite film, dissolution of debris particles and calcite cementation → quartz overgrowth, I/S and kaolinite formation → phase I oil and gas injection → dissolution of feldspar and debris particles, authigenic illite formation → quartz overgrowth, precipitation of iron-bearing carbonate cement → phase II oil and gas injection → dissolution of feldspar and carbonate cement. Since the formation of authigenic minerals and particle dissolution require a certain period, the above diagenetic phenomena will overlap.

## 5.2. Diagenetic Control on Reservoir Quality

Different diagenetic alterations mainly control the reservoir quality evolution of the Chang-7 Member sandstones during burial, such as compaction, cementation, and dissolution. Compaction and cementation are the main reasons for the densification of sandstone in the Chang-7 Member.

### (1) Impact of compaction

Compaction is an important mechanism for reducing the primary porosity of the Chang-7 Member sandstones. The lithology of the Chang-7 Member is mainly lithic arkose and feldspathic lithic sandstone, and the content of feldspar and plastic rock debris with weak compaction resistance is high. The research shows that the particles with weak anti-compaction ability are conducive to enhancing the effect of compaction [22,45–47].

Compaction is related to the burial depth of the stratum. According to the relationship between the physical properties and depth of the sandstone reservoir in the Chang-7 Member of well C96 (Figure 10), the physical properties of the reservoir tend to decrease gradually with the increase in burial depth. However, below 2060 m, the physical properties increase suddenly, indicating that the influence of compaction on the physical properties of sandstone decreases, which is largely affected by other forms of diagenesis, such as cementation and dissolution. The increase in cement precipitation and solution pores changes the law that the physical properties of a reservoir decrease with the increase in depth.

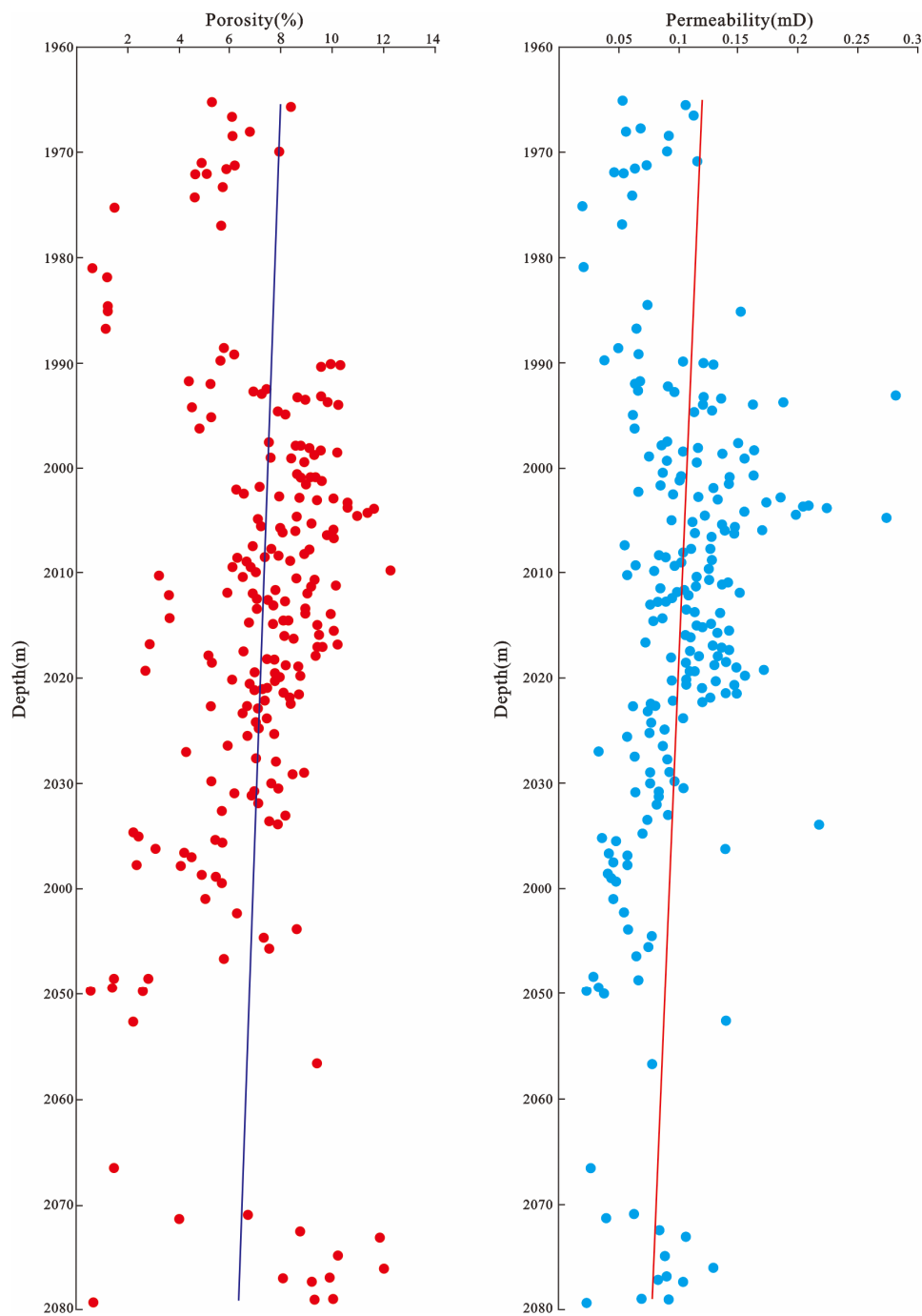


**Figure 10.** Relationship between depth and physical properties of well C96 in the Chang-7 Member.

## (2) Impact of cementation

The cement type of the Chang-7 Member in the Ordos Basin is mainly clay and carbonate minerals, followed by quartz cement. The Chang-7 Member has frequent volcanic activity, and the reservoir is rich in pyroclastic, tuff, and matrix, which provide a material basis for the formation of clay minerals [28,29,31]. At high temperatures, smectite illitization leads to high illite content. Other substances formed in the transformation process are important carbonate cement and quartz cement sources.

The authigenic illite in the Chang-7 Member fills the pores in bridging and filament shapes and forms a network when distributed intensively, which has a destructive effect on the reservoir throat. According to the correlation diagram between illite content and physical properties (Figure 11a,b), with the increase in illite content, porosity and perme-

ability show a gradually decreasing trend, showing a negative correlation. In particular, it has a great impact on permeability. The filamentous authigenic illite is easily washed and broken by high-speed fluid to block the throat, which directly reduces the permeability of the reservoir and reduces the number and radii of effective pores and throats in the reservoir [48]. Therefore, with the increase in illite content, the decreasing permeability trend is more apparent.

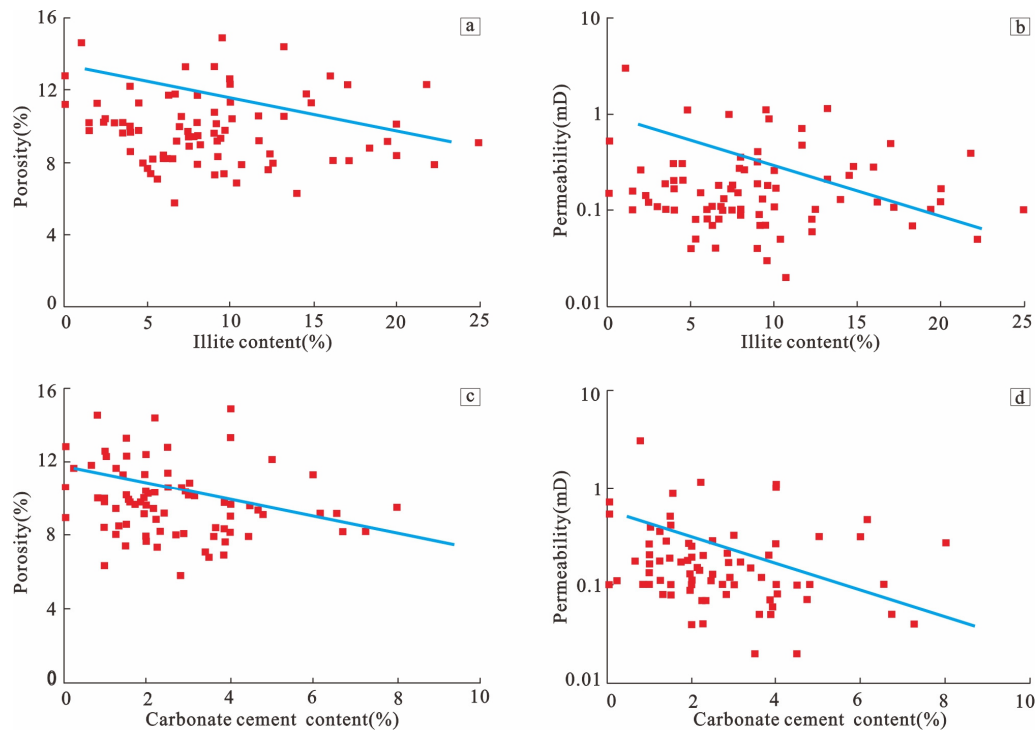


**Figure 11.** Cross-plot of the relationship between the abundance of illite cement and carbonate cement and physical properties. (a): Cross-plot of illite cement and porosity. (b): Cross-plot of illite cement and permeability. (c): Cross-plot of carbonate cement content and porosity. (d): Cross-plot of carbonate cement content and permeability.

Carbonate cement is extremely sensitive to the acidity and alkalinity of diagenetic fluid and is easy to dissolve and precipitate repeatedly. Therefore, it is a good mineral indicator of the pH change of the diagenetic environment [49]. Carbonate cementation is an important factor in pore loss in middle and late diagenesis. The number of residual pores of tight sandstones after strong compaction is small and will be gradually filled with the formation of carbonate cement.

According to the correlation diagram between the carbonate cement content and physical properties (Figure 11c,d), with the increase in carbonate cement content, porosity and permeability tend to decrease gradually, showing a negative correlation. This is because carbonate cement occupies the secondary pore space and destroys the sandstone pore system, resulting in decreasing reservoir physical properties [22,25,27].

The chart proposed by Houseknecht [50] is used to evaluate the relative importance of compaction and cementation in reducing porosity. The compaction porosity loss (COPL) and cementation porosity loss (CEPL) are statistically calculated through thin section observation. From the relationship between COPL and CEPL (Figure 12), it can be seen that cementation and compaction are of roughly the same importance in porosity failure. The statistical calculation results show that the average compaction porosity loss of sandstone in the Chang-7 Member is 15.93%, and the average cementation porosity loss is 18.67%. This shows that the effect of compaction on pore failure of the Chang-7 Member sandstone is slightly less than that of cementation.

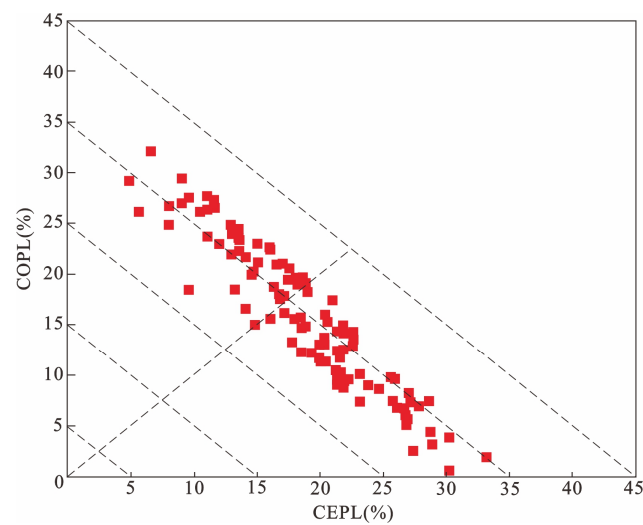


**Figure 12.** Cross-plot of COPL vs. CEPL [50].

### (3) Impact of dissolution

Dissolution is the main way to increase secondary pores and improve reservoir physical properties. Dissolution in the Chang-7 Member in the Ordos Basin includes feldspar dissolution, rock debris dissolution, and carbonate cement dissolution.

The Chang-7 Member is the most important oil generation period in the Ordos Basin. Organic acids can directly enter the adjacent sandstone to dissolve and transform the reservoir. It is evident through the relationship between the proportion of dissolved pores and the physical properties of the reservoir (Figure 13) that the number of dissolved pores is positively correlated with the porosity and permeability of the reservoir. The higher the content of dissolved pores, the greater the porosity and permeability.

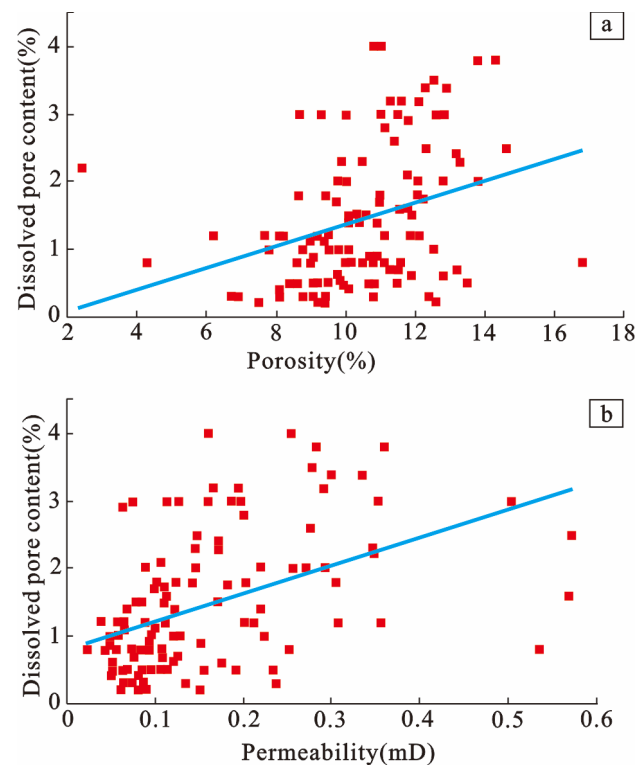


**Figure 13.** Cross-plots showing the relationship between dissolved pore content and (a) porosity and (b) permeability.

### 5.3. Diagenetic Evolution Model

According to the analysis of the source of the main authigenic minerals (carbonate cement and quartz overgrowth) and the effect of different diagenetic histories on reservoir quality, the diagenetic evolutionary model of the Chang-7 Member sandstones in the Or-dos Basin is established (Figure 14). The tight sandstone reservoir of the Chang-7 Member in the Ordos Basin experienced rapid and tight compaction and early diagenetic cementation, and the reservoir quality significantly worsened. After two stages of oil and gas filling, some clastic particles were dissolved under the action of organic acid to improve the reservoir quality. At the same time, the material formed by dissolution also provided a material source for cementation.

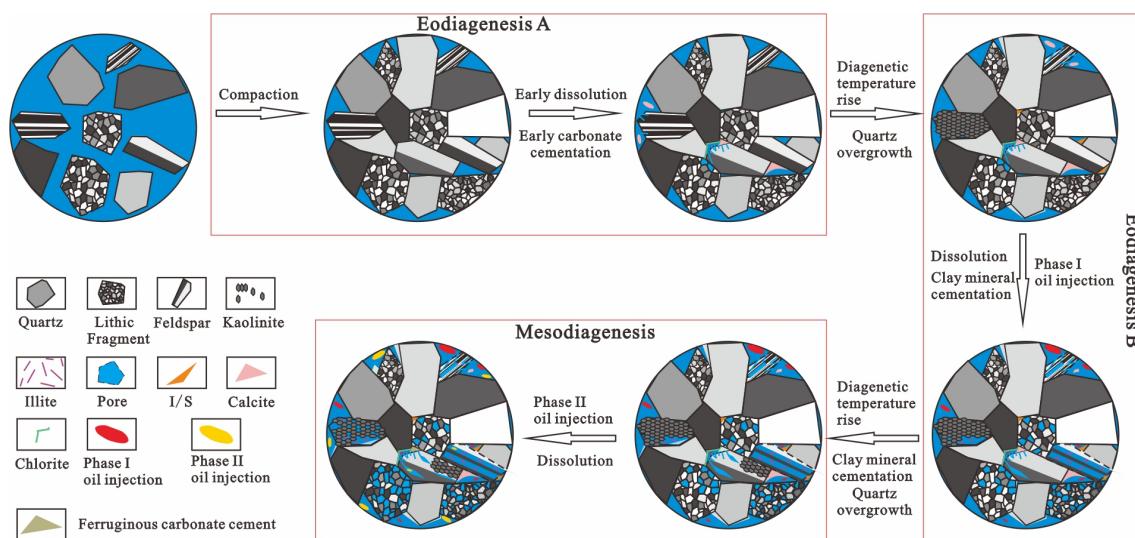


**Figure 14.** Schematic diagram showing the diagenetic evolution of tight sandstones in the Chang-7 Member of Ordos Basin [27].

### 6. Conclusions

(1) The rock types of the Chang-7 Member in the Ordos Basin are lithic arkose and feldspathic lithic sandstone. The average porosity and permeability of the reservoir are 7.17% and 0.13 mD, respectively, which is typical of a tight reservoir. The pore types are primary and secondary pore, and the pore radius is distributed between 2  $\mu\text{m}$  and 20  $\mu\text{m}$ .

(2) The diagenesis of the Chang-7 Member tight sandstone reservoir mainly includes compaction, quartz cementation, carbonate cementation, clay mineral cementation, and dissolution. Authigenic quartz, clays (illite and kaolinite), and carbonates (calcite, ferroan calcite, and ankerite) are the major pore-occluding cements.

(3) The relative time of the main diagenetic events and the mineral transformation pathway of the Chang-7 Member in the Ordos Basin show that the tight sandstone is in the middle diagenetic stage. The diagenetic sequence is as follows: compaction  $\rightarrow$  chlorite film, dissolution of debris particles and calcite cementation  $\rightarrow$  quartz overgrowth, I/S and kaolinite formation  $\rightarrow$  phase I oil and gas injection  $\rightarrow$  dissolution of feldspar and debris particles, authigenic illite formation  $\rightarrow$  quartz overgrowth, precipitation of iron-bearing carbonate cement  $\rightarrow$  phase II oil and gas injection  $\rightarrow$  dissolution of feldspar and carbonate cement.

(4) The average porosity loss of compacted and cemented tight sandstone in the Chang-7 Member is 15.93% and 18.67%, respectively. The loss of sedimentary porosity caused by cementation is greater than that caused by compaction. The pore structure is mainly controlled by authigenic minerals. Dissolution is not only improving the reservoir porosity and permeability, but also providing a material source for cementation.

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## References

- Jarvie, D.M.; Hill, R.J.; Ruble, T.E.; Pollastro, R.M. Unconventional shale-gas systems: The Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. *AAPG Bull.* **2007**, *91*, 475–499. [\[CrossRef\]](#)
- Maugeri, L. *The Shale Oil Boom: A US Phenomenon*; Harvard Kennedy School: Cambridge, MA, USA, 2013.
- Arthur, M.A.; Cole, D.R. Unconventional hydrocarbon resources: Prospects and problem. *Elements* **2014**, *10*, 257–264. [\[CrossRef\]](#)
- Karim, A.; Piper, P.G.; Piper, J.M.D. Controls on diagenesis of Lower Cretaceous reservoir sandstones in the western Sable Subbasin, offshore Nova Scotia. *Sediment. Geol.* **2010**, *224*, 65–83. [\[CrossRef\]](#)
- Dutton, P.S.; Loucks, G.R. Diagenetic controls on the evolution of porosity and permeability in lower Tertiary Wilcox sandstones from shallow to ultradeep (200–6700 m) burial, Gulf of Mexico Basin, U.S.A. *Mar. Petrol. Geol.* **2010**, *27*, 69–81. [\[CrossRef\]](#)
- Wolela, A. Diagenetic evolution and reservoir potential of the Barremian Cenomanian Debre Libanose Sandstone, Blue Nile (Abay) Basin, Ethiopia. *Cretac. Res.* **2012**, *36*, 83–95. [\[CrossRef\]](#)
- Zou, C.N.; Zhu, R.K.; Liu, K.; Su, L.; Bai, B.; Zhang, X. Tight gas sandstone reservoirs in China: Characteristics and recognition criteria. *J. Pet. Sci. Eng.* **2012**, *88*, 82–91. [\[CrossRef\]](#)
- Yuan, G.H.; Cao, Y.C.; Gluyas, J.; Li, X.Y.; Xi, K.L.; Wang, Y.Z.; Jia, Z.Z.; Sun, P.P.; Oxtoby, N.H. Feldspar dissolution, authigenic clays, and quartz cements in open and closed sandstone geochemical systems during diagenesis: Typical examples from two sags in Bohai Bay Basin, East China. *AAPG Bull.* **2015**, *99*, 2121–2154. [\[CrossRef\]](#)
- Yang, H.; Li, S.X.; Liu, X.Y. Characteristics and resource prospects of tight oil and shale oil in Ordos Basin. *Acta Pet. Sin.* **2013**, *34*, 1–11, (In Chinese with an English abstract).
- Yao, J.L.; Deng, X.Q.; Zhao, Y.D.; Han, T.Y.; Chu, M.J.; Pang, J.L. Characteristics of tight oil in Triassic Yanchang Formation, Ordos Basin. *Pet. Explor. Dev.* **2013**, *40*, 161–169. [\[CrossRef\]](#)
- Jia, C.Z.; Zou, C.N.; Li, J.Z.; Li, D.H.; Zheng, M. Evaluation criteria, major types, characteristics and resource prospects of tight oil in China. *Petrol. Res.* **2016**, *1*, 1–9. [\[CrossRef\]](#)
- Bjørlykke, K. Relationships between depositional environments, burial history, and rock properties. Some principal aspects of diagenetic process in sedimentary basins. *Sediment. Geol.* **2014**, *301*, 1–14. [\[CrossRef\]](#)
- Makeen, Y.M.; Abdullah, W.H.; Ayinla, H.A.; Hakimi, M.H.; Sia, S. Sedimentology, diagenesis and reservoir quality of the upper abu gabra formations sandstones in the Fula Sub-basin, Muglad Basin. *Sudan. Mar. Petroleum Geol.* **2016**, *77*, 1227–1242. [\[CrossRef\]](#)
- Bjørlykke, K.; Jahren, J. Open or closed geochemical systems during diagenesis in sedimentary basins: Constraints on mass transfer during diagenesis and the prediction of porosity in sandstone and carbonate reservoirs. *AAPG Bull.* **2012**, *96*, 2193–2214. [\[CrossRef\]](#)
- Schmid, S.; Worden, R.H.; Fisher, Q.J. Diagenesis and reservoir quality of the Sherwood Sandstone (Triassic), Corrib Field, Slyne Basin, west of Ireland. *Mar. Pet. Geol.* **2004**, *21*, 299–315. [\[CrossRef\]](#)
- Morad, S.; Al-Ramadan, K.; Ketzer, J.M.; Ros, L.F. The impact of diagenesis on the heterogeneity of sandstone reservoirs: A review of the role of depositional facies and sequence stratigraphy. *AAPG Bull.* **2010**, *94*, 1267–1309. [\[CrossRef\]](#)
- Rahman, M.J.; McCann, T. Diagenetic history of the Surma Group sandstones (Miocene) in the Surma Basin, Bangladesh. *J. Asian Earth Sci.* **2012**, *45*, 65–78. [\[CrossRef\]](#)
- Dai, J.X.; Ni, Y.Y.; Wu, X.Q. Tight gas in China and its significance in exploration and exploitation. *Pet. Explor. Dev.* **2012**, *39*, 277–284. [\[CrossRef\]](#)
- Yang, Q.F.; Bao, Z.D.; Wang, N.; Qu, X.F.; Lin, Y.B.; Shen, J.J.; Awan, R.S. Diagenetic evolution and its impact on reservoir quality of tight sandstones: A case study of the Triassic Chang 6 Member, Ordos Basin. *Mar. Petrol. Geol.* **2020**, *117*, 104360. [\[CrossRef\]](#)
- Sun, Z.X.; Sun, Z.L.; Lu, H.J.; Yin, X.J. Characteristics of carbonate cements in sandstone reservoirs: A case from Yanchang Formation, middle and southern Ordos basin, China. *Pet. Explor. Dev.* **2010**, *37*, 543–551. [\[CrossRef\]](#)

21. Xi, K.L.; Cao, Y.C.; Jähren, J.; Zhu, R.K.; Bjørlykke, K.; Zhang, X.X.; Cai, L.X.; Hellevang, H. Quartz cement and its origin in tight sandstone reservoirs of the Cretaceous Quantou formation in the southern Songliao basin, China. *Mar. Petrol. Geol.* **2015**, *66*, 748–753. [\[CrossRef\]](#)
22. Lai, J.; Wang, G.W.; Ran, Y.; Zhou, Z.L.; Cui, Y.F. Impact of diagenesis on the reservoir quality of tight oil sandstones: The case of Upper Triassic Yanchang Formation Chang 7 oil layers in Ordos Basin, China. *J. Petrol. Sci. Eng.* **2016**, *145*, 54–65. [\[CrossRef\]](#)
23. Dou, W.C.; Liu, L.F.; Wu, K.J.; Xu, Z.J.; Feng, X. Diagenesis of tight oil sand reservoirs: Upper triassic tight sandstones of yanchang formation in ordos basin, China. *Geol. J.* **2017**, *53*, 707–724. [\[CrossRef\]](#)
24. Yang, T.; Cao, Y.C.; Friis, H.; Liu, K.Y.; Wang, Y.Z.; Zhou, L.L.; Zhang, S.M.; Zhang, H.N. Genesis and distribution pattern of carbonate cements in lacustrine deep-water gravity-flow sandstone reservoirs in the third member of the Shahejie Formation in the Dongying Sag, Jiyang Depression, Eastern China. *Mar. Pet. Geol.* **2018**, *92*, 547–564. [\[CrossRef\]](#)
25. Xi, K.L.; Cao, Y.C.; Liu, K.Y.; Wu, S.T.; Yuan, G.H.; Zhu, R.K.; Kashif, M.; Zhao, Y.W. Diagenesis of tight sandstone reservoirs in the Upper Triassic Yanchang Formation, southwestern Ordos Basin, China. *Mar. Petrol. Geol.* **2019**, *99*, 548–562. [\[CrossRef\]](#)
26. Cui, J.W.; Zhu, R.K. Mechanism of Strong Calcium Cementation in Tight Sandstone and Its Significance: A Case Study on Triassic Chang 7 Oil Formation of Yanchang Formation in Ordos Basin. *J. Jilin Univ. (Earth Sci. Ed.)* **2020**, *50*, 957–967, (In Chinese with an English abstract).
27. Sun, N.L.; Zhong, J.H.; Hao, B.; Ge, Y.Z.; Swennen, R. Sedimentological and diagenetic control on the reservoir quality of deep-lacustrine sedimentary gravity flow sand reservoirs of the Upper Triassic Yanchang Formation in Southern Ordos Basin, China. *Mar. Petrol. Geol.* **2020**, *112*, 104050. [\[CrossRef\]](#)
28. Zhang, W.Z.; Yang, W.W.; Xie, L.Q. Controls on organic matter accumulation in the Triassic Chang 7 lacustrine shale of the Ordos Basin, central China. *Int. J. Coal Geol.* **2017**, *183*, 38–51. [\[CrossRef\]](#)
29. Fu, J.H.; Li, S.X.; Xu, L.M.; Niu, X.B. Paleo-sedimentary environmental restoration and its significance of Chang 7 Member of Triassic Yanchang Formation in Ordos Basin, NW China. *Petroleum Explor. Dev.* **2018**, *45*, 936–946. [\[CrossRef\]](#)
30. Qiao, S.H.; Li, Y.H.; Guo, W.; Zhang, Y.B.; Wang, Y. Inorganic geochemical characteristics and paleoenvironment of Chang 7 oil shale in Yanchang Formation, Tongchuan area, Shaanxi Province. *Pet Geol. Exper.* **2019**, *41*, 121–126, (In Chinese with an English abstract).
31. Li, Q.; Wu, S.H.; Xia, D.L.; You, X.L.; Zhang, H.M.; Lu, H. Major and trace element geochemistry of the lacustrine organic-rich shales from the Upper Triassic Chang 7 Member in the southwestern Ordos Basin, China: Implications for paleoenvironment and organic matter accumulation. *Mar. Pet. Geol.* **2020**, *111*, 852–867. [\[CrossRef\]](#)
32. Yu, W.; Tian, J.C.; Wang, F.; Liang, Q.S.; Yang, T.; Kneller, B.; Liang, X.W. Sedimentary environment and organic matter enrichment of black mudstones from the upper Triassic Chang-7 member in the Ordos Basin. Northern China. *J. Asian Earth Sci.* **2022**, *224*, 105009. [\[CrossRef\]](#)
33. Yang, H.; Fu, J.H.; He, H.Q.; Liu, X.Y.; Zhang, Z.Y.; Deng, X.Q. Formation and distribution of large low-permeability lithologic oil regions in Huaqing, Ordos Basin. *Petroleum Explor. Dev.* **2012**, *39*, 641–648. [\[CrossRef\]](#)
34. Dickson, J.A.D. Carbonate identification and genesis as revealed by staining. *J. Sediment. Res.* **1966**, *36*, 491–505. [\[CrossRef\]](#)
35. Moore, D.M.; Reynolds, R.C. *X-ray Diffraction and the Identification and Analysis of Clay Minerals*; Oxford University Press: Oxford, UK, 1997.
36. Hillier, S. Quantitative analysis of clay and other minerals in sandstones by X-ray powder diffraction (XRPD). In *Clay Mineral Cements in Sandstones*; Worden, R., Morad, S., Eds.; International Association of Sedimentologist, Special Publication; Blackwell Publishing Ltd.: Oxford, UK, 2003. [\[CrossRef\]](#)
37. Folk, R.L.; Andrews, P.B.; Lewis, D. Detrital sedimentary rock classification and nomenclature for use in New Zealand. *New Zeal. J. Geol. Geophys.* **1970**, *13*, 937–968. [\[CrossRef\]](#)
38. Chuhan, F.A.; Kjeldstad, A.; Bjørlykke, K.; Høeg, K. Experimental compression of loose sands: Relevance to porosity reduction during burial in sedimentary basins. *Can. Geotech. J.* **2003**, *40*, 995–1011. [\[CrossRef\]](#)
39. Wang, J.J.; Wu, S.H.; Li, Q.; Xiao, S.M. Controls of diagenetic alteration on the reservoir quality of tight sandstone reservoirs in the Triassic Yanchang formation of the Ordos Basin, China. *J. Asian Earth Sci.* **2020**, *200*, 104472. [\[CrossRef\]](#)
40. Walderhaug, O.; Bjørkum, P.A. Calcite cement in shallow marine sandstones: Growth mechanisms and geometry. In *Carbonate Cementation in Sandstones*; Morad, S., Ed.; International Association of Sedimentologists Special Publication 26; Blackwell Publishing Ltd.: Oxford, UK, 1998; pp. 179–192. [\[CrossRef\]](#)
41. Worden, R.H.; Morad, S. *Quartz Cementation in Oil Field Sandstones: A Review of the Key Controversies*; Blackwell Publishing Ltd.: Oxford, UK, 2000; pp. 1–20. [\[CrossRef\]](#)
42. de Carvalho, M.D.; Praça, U.M.; da Silva-Telles, A.C., Jr.; Jahnert, R.J.; Dias, J.L. Bioclastic carbonate lacustrine facies models in the Campos Basin (lower cretaceous), Brazil. In *Lake Basins through Space Time*; AAPG Studies in Geology; Tulsa, OK, USA, 2000. [\[CrossRef\]](#)
43. Scholle, P.A. Chalk diagenesis and its relation to petroleum exploration: Oil from chalks, a modern miracle? *AAPG Bull.* **1977**, *61*, 982–1009. [\[CrossRef\]](#)
44. SY/T 5163-2010; Analysis Method for Clay Minerals and Ordinary Non-Clay Minerals in Sedimentary Rocks by the X-ray Diffraction. China Petroleum Standardization Committee: Beijing, China, 2010. (In Chinese)
45. Ozkan, A.; Cumella, S.P.; Milliken, K.L.; Laubach, S.E. Prediction of lithofacies and reservoir quality using well logs, late cretaceous williams fork formation, mamm creek field, piceance basin, Colorado. *AAPG Bull.* **2011**, *95*, 1699–1723. [\[CrossRef\]](#)

46. Henares, S.; Caracciolo, L.; Viseras, C.; Fernandez, J.; Yeste, L.M. Diagenetic constraints on heterogeneous reservoir quality assessment: A Triassic outcrop analog of meandering fluvial reservoirs. *AAPG Bull.* **2016**, *100*, 1377–1398. [[CrossRef](#)]
47. Li, Z.; Wu, S.H.; Xia, D.L.; Zhang, X.F.; Huang, M. Diagenetic alterations and reservoir heterogeneity within the depositional facies: A case study from distributary-channel belt sandstone of Upper Triassic Yanchang Formation reservoirs (Ordos Basin, China). *Mar. Pet. Geol.* **2017**, *86*, 950–971. [[CrossRef](#)]
48. Wang, W.R.; Yue, D.L.; Zhao, J.Y.; Li, W.; Wang, B.; Wu, S.H.; Li, S.H. Diagenetic alteration and its control on reservoir quality of tight sandstones in lacustrine deep-water gravity-flow deposits: A case study of the Yanchang Formation, southern Ordos Basin, China. *Mar. Petrol. Geol.* **2019**, *110*, 676–694. [[CrossRef](#)]
49. Yao, J.L.; Wang, Q.; Zhang, R.; Tang, J.; Tian, B.; Liao, P. Origin and spatial distribution of carbonates in Yanchang Fm. (Triassic) sandstones within the lacustrine center of Ordos Basin, NW China. *Nat. Gas. Geos.* **2011**, *22*, 943–950, (In Chinese with an English abstract).
50. Houseknecht, W.D. Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG Bull.* **1987**, *71*, 633–642. [[CrossRef](#)]

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