Research Article

Evolution Mechanism of Differential Diagenesis Combination and Its Effect on the Reservoir Quality in the Tight Sandstone: A Case from the Lower Shihezi Formation in the Hangjinqi Area of Ordos Basin, China

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The physical property heterogeneity of tight sandstones was mainly caused by complex alteration of various diagenesis combinations during burial process. However, diagenetic evolution of different diagenesis combinations which generally result in the strong difference and heterogeneity of physical property and pore structure is rarely well understood. The Middle Permian lower Shihezi Formation is one of the most important tight gas sandstone reservoirs in the Hangjinqi area of Ordos Basin, China. The reservoir heterogeneity of lower Shihezi Formation, which was caused by the differential diagenesis combination, is crucial to efficient exploration and development. Evolution mechanism of differential diagenesis combination and its effect on the reservoir quality in the tight lower Shihezi Formation sandstone in the Hangjinqi area of Ordos Basin was investigated by means of thin-section description, cathodoluminescence (CL) imaging, X-ray diffraction (XRD), scanning electron microscopy (SEM), and homogenization temperature of fluid inclusions. The lower Shihezi Formation sandstones can be divided into four diagenesis combination types according to the reservoir characteristics and diagenetic relationship. The main diagenetic sequence was mechanical compaction-chlorite rim-early pore-filling calcite cementation-dissolution-authigenic kaolinite-quartz cementation-late calcite cementation. Differential diagenesis combination was mainly controlled by the petrological characteristics, microfacies, and fault. Low content of rock fragment and high content of detrital quartz were beneficial to the compaction resistance and cementation. The moderate content of pore-filling calcite was conducive to pore space protection and feldspar dissolution. The faults control dissolution and differential diagenesis combination by influencing the migration of acid fluids. Moderate compaction-moderate cementation-moderate dissolution type (BBB type) and weak compaction-moderate cementation-strong dissolution type (CBA type) were in favour of high-quality reservoir development.

1. Introduction

Reservoir quality is one of the crucial factors influencing on efficient petroleum and gas exploration of tight sandstones due to strong heterogeneity [1–4]. Tight sandstone reservoir prediction, which is generally related to diagenesis, has been a research hotspot of unconventional petroleum and gas exploration [2, 3, 5–16]. The physical property heterogeneity of tight sandstones was mainly caused by complex diagenetic interaction of various diagenesis combinations during burial process [1, 5–12]. Different diageneses, which consist of mechanical compaction, cementation, and dissolution, progressively alter porosity and permeability of tight sandstone during burial [1–3, 5, 13, 17, 18]. The controls on the
reservoir quality of various single diageneses have been well understood [1–4, 7–10]. Besides, the diagenetic facies are comprehensive description of types and degree of diagenesis including diagenetic minerals and determine the genesis and distribution of sweet spot in tight sandstones [19–22]. The types and degree of diagenesis can be defined as diagenesis combination in the tight sandstone. However, internal diagenetic evolution of different diagenesis combinations generally results in the strong difference and heterogeneity of physical property and pore structure [5, 6, 12, 22]. Tight sandstone reservoir generally experienced complex alteration of various diageneses, so that reservoir quality obviously varies in different diagenetic combinations [1, 3–6, 12, 16–18, 22, 23]. Thus, understanding evolution mechanism of differential diagenesis combination and its effect on the reservoir quality in the tight sandstone is critical for reservoir quality prediction of the tight sandstones.

The Middle Permian lower Shihze Formation is one of the most important tight gas sandstone reservoirs in the Hangjinqi area of Ordos Basin, China [24, 25]. The tight sandstone of the lower Shihze Formation has generally undergone complicated diagenetic alterations which have reduced the reservoir quality. Previous studies merely involved deposition, diagenesis, and their impacts on the reservoir quality [26–28]. This study is aimed at understanding the evolution mechanism of differential diagenesis combination and its effect on the reservoir quality in the tight sandstone belonging to the Middle Permian lower Shihze Formation, Hangjinqi area, Ordos Basin, China, in order that the reservoir quality can be forecast ahead of drilling in unexplored regions of the basin.

2. Geological Setting

The Ordos Basin, which is the second largest sedimentary basin in China, is located in northcentral China (Figure 1(a)) [29]. Hangjinqi area is situated in the transitional zone between Yimeng Uplift and Yishan Slope of northern Ordos Basin (Figures 1(b) and 1(c)) [30, 31]. The Yanshanian orogeny ended sedimentation in the basin at the close of the Early Cretaceous [30]. The Paleozoic and Mesozoic sedimentary rocks were folded into a north–trending synclinorium owing to the Yanshanian and Himalayan orogenies [30–34]. There are two nearly east–west trending faults and one northeast–southwest trending fault due to tectonic movements (Figure 1(c)) [30–34].

The Middle–Upper Ordovician to the lower part of Carboniferous are missing owing to widespread uplifting and erosion across the North China block as the result of Caledonian movement in the early Paleozoic [35]. The upper Carboniferous mainly consists of the Benxi Formation. The lower Permian comprises the Taiyuan Formation (P1t) and Shanxi Formation (P1s). The middle Permian includes the lower Shihze (P1h) and upper Shihze Formation (P1s). The upper Permian comprises Shiquanfeng Formation (P2s) [24, 25, 36] (Figure 2). The lower Shihze Formation, which mainly consists of tight sandy conglomerates, pebbly coarse-, coarse-, medium-, and fine-grained sandstones, was mainly deposited in fluvial and delta [26, 37, 38] (Figure 2).

The first member (H1) of lower Shihze Formation, which was mainly deposited in the braided river, is the main reservoir of study area (Figure 2) [26, 37, 38]. The meandering river of the second member (H2) evolved into the delta of the third member (H3) in the Hangjinqi area [26, 37, 38]. The lower Shihze Formation has huge potential for producing tight sandstone gas in China [32, 27 28] (Figure 2).

3. Samples and Methods

The well logs and conventional cores were collected from the Exploration and Development Research Institute of North China Branch Company of Sinopec.

Eighty sandstone samples of lower Shihze Formation were collected from the drill cores of 4 wells (Figure 1(c)), in which 74 thin sections were impregnated with blue epoxy resin and prepared for petrological and diagenetic studies by 300-point count. Porosity of different pore types and volume content of different cements can be calculated under thin section by image quantitative analysis with the Photoshop software [11, 12].

Thirteen representative samples, which were coated with gold, were analyzed under a Quanta250 FEG scanning electron microscope (SEM and BSD) equipped with an energy-dispersive (ED) spectroscope in order to examine authigenic minerals and pore geometry and diagenetic sequence in the sandstones.

X-ray diffraction (XRD) analysis of whole rock was performed on 30 core samples to identify types and contents of major minerals. The relative contents of different clay minerals and I/S mixed-layer ratios of 30 core samples were determined by XRD analysis of quantitative clay minerals. These two experiments were completed by using an Ultima IV X-ray diffractometer under the condition of 25°C temperature and 50% humidity. Cathodoluminescence (CL) analyses were performed on the 4 typical core samples with high content of carbonate cement (>2%) under an Olympus microscope equipped with a CL8200-MKS CL instrument. Homogenization temperature of fluid inclusions within calcite cement of two core samples with carbonate cement (more than 5%) was determined under a petrographic microscope equipped with a Linkam.

4. Results

4.1. Petrology of Sandstones. The lower Shihze Formation sandstones in the Dongshen gas field are predominantly litharenite according to Folk’s sandstone classification scheme [39], averaged as Q1.1F1.8R1.0 (Figure 3). Detrital quartz (Q), which is the most common detrital composition, varies from 24.7% to 76.6% of the detrital grain volume with an average value of 51.2%. Rock fragments, which consist of volcanic, metamorphic, and minor sedimentary rock fragments (Figures 4(a)–4(f)), vary from 19.5% to 74.1% of the detrital grain volume with an average value of 45% (Figure 3). Volcanic rock fragments mainly comprise neutral–basic extrusive rock (Figure 4(e)). Feldspars, which range from 1.1% to 8.1% of the detrital grain volume with an average of 3.8% (Figure 3), comprise plagioclase and...
minor K-feldspar. The detrital grains are poorly to moderately sorted and medium and medium-coarse grained, with some amounts of coarse grained and conglomeratic coarse grained (Figures 4(a)–4(i)).

4.2. Pore Types, Porosity, and Permeability of Sandstones. The pore space of lower Shihezi Formation sandstone consists of secondary dissolved pore, minor microfracture, and primary pore (Figure 5). Secondary dissolved pores, which were formed by the dissolution of feldspar and volcanic rock fragments, mainly consist of intragranular dissolved pores (Figures 5(a)–5(l)) and minor intergranular dissolved pore (Figures 5(a) and 5(k)). The pore space generally occurs with calcite cement (Figures 5(b)–5(k)). Intragranular dissolved pores are secondary dissolved pores that form around primary pores of the sandstone. The secondary dissolved pores are primary microfractures (mineral dissolution, mechanical dissolution, and bacterial dissolution) (Figures 5(a)–5(l)) and secondary microfractures (Figures 5(a) and 5(k)).
pores, intergranular dissolved pore, and microfracture approximately occupy 75%, 20%, and 5%, respectively, in the total pore space (Figures 5(a) and 5(b)). The core porosity of lower Shihezi Formation sandstone mainly ranges from 6% to 14% (av. 9.58%), and the core permeability generally ranges from 0.01 to 1 mD (av. 0.63 mD) (Figure 6). There is only weak correlation relationship between porosity and permeability of lower Shihezi Formation sandstone (Figure 7).

4.3. Diagenetic Minerals and Reactions. The diagenetic alterations mainly comprise mechanical compaction, cementation, clay mineral transformation, and dissolution in the lower Shihezi Formation sandstones of study area (Figures 8(a)–8(f)).

4.3.1. Compaction. Framework grains are generally heavily mechanically compacted, which are proved by major long and minor concave-convex grain contacts in the lower Shihezi Formation sandstones (Figures 8(a) and 9(a)–9(c)).
Direct evidence of mechanical compaction is the deformation of mica and plastic rock fragments (Figures 8(a) and 9(a)–9(c)). Chemical compaction, pressure dissolution, is locally observed as the concave-convex and sutured contacts (Figure 9(c)).

4.3.2. Carbonate Cements. Authigenic minerals in lower Shihezi Formation sandstones mainly consist of carbonate, clay mineral, and some quartz cements (Figures 5 and 8–10). Carbonate cements, which mainly comprise calcite, are the dominant cement in the lower Shihezi Formation sandstones (Figures 9 and 10). Calcite cements vary from 0.5 vol%–20 vol% with an average of 4.86% (thin-section observation). Calcite cements mainly fill in the pore (Figures 8(b), 9(d), 9(h), 9(l), and 10(a)–10(d)) and partly replace the detrital feldspar (Figures 5(b)–5(f), 5(h), 5(k), 9(b), 9(d), 9(e), 9(g), 9(h), and 10(a)–10(d)). The pore-filling calcite ranges from 2% to 18 vol% with an average of 6.55 vol%. The calcite, which occurs as replacement of detrital, makes up 0.5%–7% with an average of 2.4 vol%. There is no obvious difference between the pore-
Figure 5: Pore space types and calcite characteristics of the lower Shihezi Formation sandstones in the study area. (a) Feldspar was dissolved into intergranular dissolved pore (FED), intragranular dissolved pore (FAD), and mold pore (FZD), and some fragment was dissolved into mold pore (RZD), well J51, H1-2, 2722.52 m; (b) feldspar was dissolved into mold pore (FZD) and replaced by calcite (CAR), well J51, H1-2, 2721.97 m; (c) feldspar was dissolved into intragranular dissolved pore (FAD) and replaced by calcite (CAR), well J51, H1-2, 2726.02 m; (d) volcanic rock fragment (VF) was dissolved into intragranular dissolved pore (RAD) and replaced by calcite (CAR), well J51, H1-2, 2726.02 m; (e) feldspar was dissolved into intragranular dissolved pore (FAD) and replaced by calcite (CAR), microfracture (MF), well J51, H1-2, 2727.76 m; (f) feldspar was dissolved into intragranular dissolved pore (FAD) and replaced by calcite (CAR), and pores were filled with pore-filling calcite (CAR), well J104, H1-2, 2679.44 m; (g) feldspar was dissolved into intragranular dissolved pore (FAD) and replaced by calcite (CAR), and pores were filled with pore-filling calcite (CAR), well J104, H1-2, 2679.44 m; (h) feldspar was dissolved into intragranular dissolved pore (FAD) and replaced by calcite (CAR), and volcanic rock fragment (VF) was dissolved into intragranular dissolved pore (RAD), well J104, H1-2, 2682.13 m; (i) feldspar was dissolved into intragranular dissolved pore (FAD), well J104, H1-2, 2695.01 m; (j) volcanic rock fragment (VF) was dissolved into intergranular dissolved pore (FED) and intragranular dissolved pore (FAD), well J77, H1-1 2707.58 m; (l) microfracture (MF), well J77, H1-1, 2748.28 m.
filling calcite and calcite replacing detrital (Figures 10(b) and 10(d)). Homogenization temperatures within calcite cement are mainly distributed in the 100-120°C and minor 120-130°C in the lower Shihezi Formation sandstones (Figures 11(a)–11(c)).

4.3.3. Quartz Cements. Quartz cements mainly occur as the pore-filling quartz (Figure 8(m)) and quartz overgrowth (Figures 8(n), 9(c), 10(a), and 10(c)). Authigenic quartz generally occurs with feldspar dissolution (Figures 9(c) and 10(a)).

4.3.4. Clay Minerals. Authigenic clay minerals mainly comprise with the kaolinite (Figures 8(d), 8(g), and 8(l)), chlorite (Figures 8(e) and 8(m)), illite (Figures 8(c), 8(g), and 8(l)), and mixed layer of illite/smectite (Table 1). The relative content of smectite in the illite/smectite mixed layer is approximately 20% (Table 2). Authigenic chlorite mainly comprises pore-filling chlorite (Figure 8(e)) and chloride coating (Figure 8(m)). Transformation processes of clay minerals mainly include the kaolinitization of feldspar, illitization of kaolinite, and chloritization of kaolinite (Table 2 and Figures 8(d), 8(g), and 8(l)). The illite and kaolinite generally occur with feldspar dissolution (Figures 8(k) and 8(l)).

4.3.5. Dissolution. Major feldspars and minor volcanic rock fragments were pervasively dissolved in the studied sandstones, which generally produced secondary pores (Figure 5). The plagioclase and some K-feldspar were dissolved partially or totally (Figure 5).

4.4. Diagenesis Combination. The compaction can be divided into weak (point contact), moderate (spot-line act), and strong (line contact) types according to grain contact relationship. Cementation can be divided into weak, moderate, and strong types according to content of calcite cement. Dissolution can be divided into weak, moderate, and strong types according to thin-section porosity of secondary pore. The lower Shihezi Formation sandstones can be divided into four diagenesis combination types according to the reservoir characteristics and diagenetic relationship.

(1) Strong compaction-weak cementation-weak dissolution type (ACC type)

Strong compaction was indicated by the dominance of long and some concave-convex grain contacts and deformation of mica and plastic rock fragments. Weak cementation was manifested by the low content of pore-filling calcite cement (less than 3 vol%) (Table 3). The thin-section porosity of secondary pore is generally less than 2%, which suggested that weak dissolution (Table 3). The relative quartz contents of ACC sandstones vary from 24.7% to 67.4% with an average of 46.4% (Table 4 and Figure 12(a)). Feldspar contents range from 1.1% to 5.6% with an average of 3.3% (Table 4 and Figure 12(b)). Rock fragment contents vary from 30.4% to 74.1% with an average of 50.3% (Table 4 and Figure 12(c)). The tight ACC sandstones comprise poorly to moderately sorted detrital grains. The matrix contents are generally more than 5% (Table 3). The ACC type mainly occurs in the distributary channel and minor braided channel microfacies (Table 4). The ACC types were mainly observed in the well J77, well J104, and well J51 (Figure 13).

(2) Weak compaction-strong cementation-weak dissolution type (CAC type)

Weak compaction was indicated by the dominance of point and point-long grain contacts, grain-support, and
Figure 8: Diagenetic characteristics (SEM images) of the lower Shihezi Formation sandstones in the study area. (a) Strong compaction with few pores, well J77, H3-1, 2618.51 m; (b) calcite cement filling in the pores (CAP), well J77, H1-2, 2690.2 m; (c) authigenic illite, well J77, H1-2, 2690.2 m; (d) page-like authigenic kaolinite (Kao) and intercrystal pore (ICP), well J77, H1-2, 2690.2 m; (e) authigenic chlorite and illite, well J77, H1-2, 2692.57 m; (f) intergranular dissolved pore (FAD), well J77, H1-2, 2696.86 m; (g) authigenic chlorite and illite, well J16, H1-3, 2350.67 m; (h) intragranular dissolved pore of feldspar (FAD), well J16, H1-3, 2350.67; (i) intragranular dissolved pore of rock fragment (RAD), well J16, H1-3, 2351.3 m; (j) feldspar was dissolved into intragranular dissolved pore (FAD) and replaced by calcite (CAR), well J16, H1-3, 2353.14 m; (k) dissolution (FAD) and illitization of feldspar, well J16, H1-3, 2355.56 m; (l) feldspar was dissolved into intragranular dissolved pore (FAD) and kaolinite, and kaolinite was replaced by illite, well J16, H1-3, 2355.56 m; (m) chlorite rim (Chl-R) and authigenic quartz (AQP), well J16, H1-3, 2361.52 m; (n) quartz overgrowth (AQW), well J24, H1-1, 2463.56 m; (o) feldspar was dissolved into mold pore (FZD), well J24, H1-1, 2463.56 m.
partial matrix-support. Strong cementation was manifested by the high content of pore-filling calcite cement (more than 10 vol%) (Table 3). The thin-section porosity of secondary pore is generally less than 2%, which suggested weak dissolution (Table 3). The relative quartz contents of CAC sandstones vary from 72% to 76.6% with an average of 74.3% (Table 4 and Figure 12(a)). Feldspar contents range from 3.7% to 3.9% with an average of 3.8% (Table 4 and Figure 12(b)). Rock fragment contents vary from 19.5% to 24.4% with an average of 21.9% (Table 4 and Figure 12(c)). The tight CAC sandstones comprise moderately to well-sorted detrital grains moderately and minor poorly sorted detrital grains. The CAC type mainly occurs in the distributary channel microfacies (Table 4).

(3) Moderate compaction-moderate cementation-moderate dissolution type (BBB type)

Moderate compaction was proved by the major point-long and some long grain contacts and grain-support. Moderate cementation was manifested by the moderate content of pore-filling calcite cement (3-10 vol%) (Table 3). The thin-section porosity of secondary pores generally varies from 2% to 4%, which suggested moderate dissolution (Table 3). The relative quartz contents of BBB sandstones vary from 40.4% to 61.4% with an average of 52.5% (Table 4 and Figure 12(a)). Feldspar contents range from 2.2% to 6.9% with an average of 4.2% (Table 4 and Figure 12(b)). Rock fragment contents vary from 34.5% to 56.2% with an average

Figure 9: Compaction and calcite cementation of the lower Shihezi Formation sandstones in the study area. (a) Plastic deformation of phyllite rock fragment (PF), well J51, H1-2, 2724.55 m; (b) plastic deformation of mica (MC), well J51, H1-2, 2723.87 m; (c) intragranular dissolved pore of feldspar (FED) and quartz overgrowth (AQW), well J51, H1-2, 2721.97 m; (d) pore-filling calcite (CAP) and calcite as replacement of feldspar (CAR), well J51, H1-2, 2723.87 m; (e) calcite as replacement of feldspar (CAR), well J104, H1-1, 2695.49 m; (f) pore-filling calcite (CAP) and calcite as replacement of feldspar (CAR) with dissolution (FED), well J104, H2-1, 2638.96 m; (g) pore-filling calcite (CAP) and calcite as replacement of feldspar (CAR), well J104, H1-2, 2723.87 m; (h) pore-filling calcite (CAP) and calcite as replacement of feldspar (CAR), well J104, H1-2, 2679.44 m; (i) pore-filling calcite (CAP), well J104, H1-2, 2679.44 m.
of 43.3% (Table 4 and Figure 12(c)). The BBB sandstones comprise moderately and minor poorly sorted detrital grains. The BBB type mainly occurs in the distributary channel microfacies (Table 4). The BBB type mainly occurs within the first member (H1) of lower Shihezi Formation of the well J24 and well J104 (Figure 13).

Figure 10: Calcite cementation (cathode luminescence images) of the lower Shihezi Formation sandstones in the study area. (a, b) Pore-filling calcite (CAP) showing orange, orange red calcite as replacement of feldspar (CAR), and quartz overgrowth (AQW), well J77, H1-2, 2696.86 m; (c, d) orange red calcite as replacement of feldspar (CAR) and quartz overgrowth (AQW), well J77, H1-2, 2703.87 m.

Figure 11: Homogenization temperature of the lower Shihezi Formation sandstones in the study area. (a) Fluid inclusion within calcite cement, well J104, 2656.48 m; (b) fluid inclusion within calcite cement, well J104, 2674.98 m; (c) the homogenization temperature distribution within calcite cement of the lower Shihezi Formation sandstones.
(4) Weak compaction-moderate cementation-strong dissolution type (CBA type)

Weak compaction was indicated by the dominance of point and point-long grain contacts, grain-support, and partial matrix-support. Moderate cementation was manifested by the moderate content of pore-filling calcite cement (3-10 vol%) (Table 2). The thin-section porosity of secondary pores is generally more than 4%, which suggested strong dissolution (Table 2). The relative quartz contents of CBA sandstones vary from 48.8% to 75.5% with an average of 61.6% (Table 4 and Figure 12(a)). Feldspar contents range from 1.1% to 7.5% with an average of 4.7% (Table 4 and Figure 12(b)). Rock fragment contents vary from 21.3% to 47.2% with an average of 33.8% (Table 4 and Figure 12(c)). The CBA sandstones comprise moderately to well-sorted detrital grains. The matrix contents are generally less than 2% (Table 3). The CBA type mainly occurs in the distributary channel and minor braided channel microfacies (Table 4). The CBA type mainly occurs within the first member (H1) of the well J51, well J24, well J94, and well J104 (Figure 13). In general, the BBB type and CBA type were mainly distributed in the wells near the fault (Figures 1 and 13).

5. Discussion

5.1. Evolution Mechanism of Differential Diagenetic Combination

5.1.1. Genesis and Sequence of Diagenesis

(1) Genesis of Diagenesis. The pore-filling calcite ranges from 2% to 18 vol% with an average of 6.55 vol%, which suggests that the pore-filling calcite was mainly precipitated from the pore fluids. The homogenization temperature of fluid inclusions within calcite cement also indicates that the pore-filling calcite was mainly precipitated at the eodiagenetic and early mesodiagenetic stages. Calcite replacing detrital grains generally occur with dissolution (Figures 5(f) and 5(h)), which indicates that replacement of calcite was related with dissolution.

The dissolution was mainly determined by feldspars, minor volcanic rock fragments, and acid fluids (Figure 5). Besides, the BBB type and CBA type were mainly distributed in the wells near the fault (Figures 1 and 13), because the fault is the main migration path for acid fluids [3, 5, 11, 12]. Besides, the dissolution can provide diagenetic environment and material basis for the calcite replacing detrital grains.

(2) Diagenesis Sequence. The clay mineral characteristics (20% smectite in the illite/smectite mixed layer) and burial depth (2000 m-3000 m) suggested that the lower Shihezi Formation sandstones were mainly at mesodiagenetic stage. Relative diagenetic sequence can be determined according to petrographic evidences from thin section, cathodoluminescence (CL), and scanning electron microscope (SEM) analysis. Besides, the formation period of calcite cement can be calculated by homogenization temperature of fluid inclusions within calcite cement. The main diagenetic sequence was mechanical compaction-chlorite rim-early pore-filling calcite cementation-dissolution-authigenic kaolinite-quartz cementation-late calcite cementation (Figure 14). On the basis of previous burial and thermal history studies, the diagenetic sequence of the lower Shihezi Formation sandstones can be reconstructed and illustrated in Figure 13 [27, 28].

Table 1: Homogenization temperature within calcite cement in the lower Shihezi Formation sandstones of the study area.

| Well | Samples | Stratum | Depth (m) | Cement | Homogenization temperature (°C) |
|------|---------|---------|-----------|--------|---------------------------------|
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 108                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 104                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 112                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 106                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 108                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 104                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 106                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 100                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 105                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 110                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 115                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 110                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 128                             |
| J104 | J104-3-1-1 | H1-3   | 2656.48 | Calcite | 125                             |
| J104 | J104-5-2-1 | H1-2   | 2674.98 | Calcite | 126                             |
| J104 | J104-5-2-1 | H1-2   | 2674.98 | Calcite | 116                             |
| J104 | J104-5-2-1 | H1-2   | 2674.98 | Calcite | 120                             |
| J104 | J104-5-2-1 | H1-2   | 2674.98 | Calcite | 110                             |
| J104 | J104-5-2-1 | H1-2   | 2674.98 | Calcite | 118                             |
| J104 | J104-5-2-1 | H1-2   | 2674.98 | Calcite | 114                             |
5.1.2. Controlling Factors of Differential Diagenesis Combination

(1) Petrological Characteristics of Sandstones. The average quartz content of ACC type is obviously less than the BBB, CAC, and CBA types, whereas the rock fragment of ACC type is more than other three types (Figure 12). This suggests that the mechanical compaction was mainly influenced by the contents of detrital quartz and rock fragment (Figure 15). CAC and CBA have less rock fragment and more detrital quartz than the ACC and BBB types, which indicate that low content of rock fragment and high content of detrital quartz were beneficial to the compaction resistance and cementation (Figure 15). The CBA and BBB have more feldspar than the ACC and CAC, which suggests that feldspar was the important dissolution object (Figure 12(b)). The ACC sandstone has poorly sorted grains than the other three types, which indicates that mechanical compaction was also controlled by the textural characteristics (Table 4).

(2) Microfacies. The CAC, BBB, and CBA types mainly occur in the distributary channel microfacies of delta plain.

| No | Well | Depth (m) | Stratum | Illite | Kaolinite | Chlorite | I/S mixture layer | C/S mixture layer | Illite ratio within I/S mixture layer (%) |
|----|------|-----------|---------|--------|-----------|----------|-------------------|-------------------|------------------------------------------|
| 1  | J107 | 3182.82   | H1-2    | 56     | 8         | 23       | 13                | 0                 | 15                                       |
| 2  | J107 | 3196.99   | H1-2    | 36     | 7         | 52       | 5                 | 0                 | 10                                       |
| 3  | J108 | 3087.7    | H3-2    | 7      | 4         | 56       | 33                | 0                 | 30                                       |
| 4  | J108 | 3154.52   | H1-3    | 33     | 5         | 27       | 35                | 0                 | 15                                       |
| 5  | J113 | 3071.66   | H1-3    | 21     | 7         | 59       | 13                | 0                 | 25                                       |
| 6  | J113 | 3082.7    | H1-2    | 28     | 10        | 26       | 36                | 0                 | 15                                       |
| 7  | J113 | 3106.32   | H1-1    | 13     | 38        | 38       | 11                | 0                 | 15                                       |
| 8  | J11  | 2097.56   | H3-1    | 17     | 33        | 39       | 11                | 0                 | 10                                       |
| 9  | J11  | 2129.02   | H2-1    | 32     | 25        | 22       | 21                | 0                 | 30                                       |
| 10 | J11  | 2136.45   | H2-1    | 34     | 22        | 24       | 20                | 0                 | 30                                       |
| 11 | J11  | 2161.04   | H1-3    | 34     | 15        | 39       | 12                | 0                 | 10                                       |
| 12 | J11  | 2173.53   | H1-2    | 37     | 14        | 38       | 11                | 0                 | 10                                       |
| 13 | J11  | 2185.07   | H1-1    | 11     | 33        | 43       | 13                | 0                 | 10                                       |
| 14 | J5   | 2601.74   | H3-2    | 10     | 21        | 47       | 22                | 0                 | 35                                       |
| 15 | J5   | 2658.49   | H1-3    | 19     | 25        | 48       | 8                 | 0                 | 10                                       |
| 16 | J76  | 2693.72   | H1-1    | 18     | 30        | 33       | 19                | 0                 | 20                                       |
| 17 | J77  | 2618.51   | H3-1    | 16     | 32        | 35       | 17                | 0                 | 20                                       |
| 18 | J77  | 2690.2    | H1-2    | 17     | 30        | 35       | 18                | 0                 | 20                                       |
| 19 | J77  | 2709.79   | H1-1    | 15     | 31        | 34       | 17                | 0                 | 20                                       |
| 20 | J89  | 3082.34   | H1-2    | 29     | 21        | 10       | 40                | 0                 | 25                                       |
| 21 | J89  | 3088.17   | H1-2    | 15     | 32        | 33       | 20                | 0                 | 25                                       |
| 22 | J92  | 3027.32   | H1-4    | 15     | 25        | 42       | 18                | 0                 | 20                                       |
| 23 | J92  | 3031.10   | H1-3    | 15     | 26        | 39       | 20                | 0                 | 20                                       |
| 24 | J92  | 3061.25   | H1-1    | 16     | 28        | 36       | 20                | 0                 | 20                                       |
| 25 | J92  | 3066.10   | H1-1    | 15     | 30        | 35       | 20                | 0                 | 20                                       |
| 26 | J92  | 3073.26   | H1-1    | 9      | 80        | 10       | 20                | 0                 | 20                                       |
| 27 | J95  | 3086.18   | H3-2    | 7      | 4         | 33       | 56                | 0                 | 30                                       |
| 28 | J95  | 3112.85   | H3-1    | 6      | 3         | 59       | 32                | 0                 | 30                                       |
| 29 | J95  | 3114.05   | H3-1    | 5      | 9         | 4        | 82                | 0                 | 50                                       |
| 30 | J95  | 3116.48   | H3-1    | 11     | 5         | 64       | 20                | 0                 | 30                                       |
| 31 | J95  | 3206.03   | H1-1    | 11     | 39        | 20       | 20                | 0                 | 30                                       |
| 32 | J95  | 3208.77   | H1-1    | 14     | 28        | 50       | 8                 | 0                 | 25                                       |
| 33 | J97  | 2321.24   | H2-1    | 15.00  | 27.00     | 35.00    | 23.00             | 0                 | 20                                       |
| 34 | J97  | 2331.66   | H2-1    | 8.00   | 82.00     | 0        | 10.00             | 0                 | 20                                       |
| 35 | J97  | 2338.22   | H1-4    | 14.00  | 40.00     | 27.00    | 19.00             | 0                 | 25                                       |
| 36 | J103 | 3092.15   | H1-2    | 10     | 0         | 68       | 22                | 0                 | 25                                       |
ACC type mainly occurs in the distributary channel and minor braided channel microfacies. These suggest that distributary channel was in favour of preservation of pore and cementation, and distributary channel and braided channel microfacies may enhance the mechanical compaction (Table 4).

(3) Fault and Fracture and Source Rock. The shorter distance between the fault and well, the CBA and BBB, were more developed (Figures 1 and 13). Besides, the CBA type and BBB type mainly occur within the first member (H1) sandstone, which is closed to the underlying source rock of Shanxi Formation (Figure 2). This indicates that the dissolution and differential diagenesis combination were influenced by the fault and source rock, because the fault is the key migration path for acid fluids released by source rock [3, 5, 11, 12].

5.1.3. Genetic Mechanism of Differential Diagenesis Combination

(1) Strong Compaction-Weak Cementation-Weak Dissolution Type (ACC Type). The strong compaction of ACC type sandstone almost destroyed all primary pores, so that there were not enough pores for the cementation. The tight ACC type sandstone, which was mainly caused by the strong compaction and weak cementation, was not beneficial for the organic acid flow and dissolution (Figure 14).

(2) Weak Compaction-Strong Cementation-Weak Dissolution Type (CAC Type). Many primary pores can be preserved by chlorite coating, the weak compaction as result of high content of detrital quartz and low content of rock fragment of distributary channel. Many residual primary pores provided enough space for strong calcite cementation, so that almost all primary pores were occupied by the calcite cement. The strong calcite cementation generally restrained organic acid flow and dissolution. Therefore, the densification of CAC type sandstone was mainly influenced by the strong cementation and weak dissolution (Figure 14).

(3) Moderate Compaction-Moderate Cementation-Moderate Dissolution Type (BBB Type). Some primary pores can be preserved by the chlorite coating, moderate compaction as result of middle content of detrital quartz, middle content of rock fragment, and moderately sorted detrital grains of distributary channel. These residual primary pores can provide some space for the moderate calcite cementation. Besides, moderate content of calcite cements can protect primary pores from destruction of mechanical compaction, which can also provide channel for organic acid flow and moderate dissolution (Figure 14).

(4) Weak Compaction-Moderate Cementation-Strong Dissolution Type (CBA Type). Many primary pores can be preserved by the weak compaction as result of high content of detrital quartz and low content of rock fragment of distributary channel. Many residual primary pores provided enough space for calcite cementation, so that many primary pores were occupied by the calcite cement. However, moderate

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**Table 3:** Diagenetic characteristics of main diagenesis combination types in the lower Shihezi Formation sandstones of the study area.

| Diagenesis combination | Compaction (grain contacts) | Cementation (calcite) | Dissolution |
|------------------------|-----------------------------|-----------------------|-------------|
| ACC type               | Long and some concave-convex grain contacts and deformation of mica and plastic rock fragments, matrix contents are more than 5% | Pore-filling calcite cement content is less than 3%. | Thin-section dissolved porosity is less than 2%. |
| CAC type               | Point and point-long grain contacts | Pore-filling calcite cement content is more than 10%. | Thin-section dissolved porosity is less than 2%. |
| BBB types              | Point-long and minor long grain contacts, matrix contents vary from 2% to 5% | Calcite cement, which mainly comprises pore-filling calcite and minor replacement, varies from 3% to 10%. | Thin-section dissolved porosity varies from 2% to 4%. |
| CBA type               | Point and point-long grain contacts, grain-support, and partial matrix-support, matrix contents are less than 2%-5% | Calcite cement, which mainly comprises pore-filling calcite and minor replacement, varies from 3% to 10%. | Thin-section dissolved porosity is more than 4%. |

**Table 4:** Composition and texture characteristics of main diagenesis combination types in the lower Shihezi Formation sandstones of the study area.

| Diagenesis combination | Detrital quartz (%) | Detrital feldspar (%) | Rock fragment (%) | Sorting characteristics | Microfacies |
|------------------------|---------------------|-----------------------|-------------------|-------------------------|-------------|
| ACC                    | 40.4                | 52.5                  | 2.2               | 4.2                     | Weak-moderate | Distributary channel |
| BBB                    | 72.6                | 3.7                   | 3.9               | 3.8                     | Moderate-well | Distributary channel |
| CAC                    | 48.8                | 61.6                  | 1.1               | 7.5                     | Moderate-well | Distributary channel |
| CBA                    | 24.7                | 46.4                  | 1.1               | 5.6                     | Moderate-weak | Distributary channel |
|                        | 30.4                | 50.3                  | 19.5              | 21.9                    | Moderate-well | Distributary channel |
|                        | 21.3                | 33.8                  | 35.6              | 43.3                    | Moderate-well | Distributary channel |

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content of calcite cements can protect primary pores from strong destruction of mechanical compaction and calcite cementation. Therefore, the residual primary pores were beneficial for the organic acid flow and strong dissolution (Figure 14).

5.2. Effect of Differential Diagenesis on the Reservoir Quality.

The higher content of detrital quartz, the higher calcite cement (Figure 14(a)) or higher thin-section porosity (Figure 15(b)). Besides, the moderate content of pore-filling calcite (3-10%) can protect the primary pore from
destruction of mechanical compaction (Figures 14 and 16(a)). However, calcite replacing detrital grains have positive relation with thin-section porosity (Figure 16(b)), which indicates that replacement of calcite was related with dissolution (Figure 14). Besides, the calcite cement generally appears with secondary pores and feldspar dissolution (Figures 5(b)–5(k)). This indicates moderate content of pore-filling calcite was beneficial for pore space protection and feldspar dissolution (Figure 14). Therefore, CAC type was characterized by the high content of detrital quartz and calcite, which resulted in weak dissolution. The BBB type has experienced moderate compaction due to middle content of detrital quartz and calcite cement, which resulted in the moderate dissolution. The CBA type has more dissolved pores due to the moderate calcite cement and strong dissolution. In a word, the BBB and CBA type sandstones were in favour of reservoir development (Figure 14).

*Figure 14: Diagenetic sequence and reservoir evolution of the lower Shihezi Formation sandstones in the study area (burial history was modified from Qiu et al. [27]).*
6. Conclusions

This study of the lower Shihezi Formation sandstones in the Hangjinqi area of Ordos Basin, China, yields important clues about differential diagenetic combination and its effect on the reservoir quality in the tight fluvial sandstone, including the following:

(1) The lower Shihezi Formation sandstones mainly comprise four diagenesis combination types: strong compaction-weak cementation-weak dissolution type (ACC type), weak compaction-strong cementation-weak dissolution type (CAC type), moderate compaction-moderate cementation-moderate dissolution type (BBB type), and weak compaction-moderate cementation-strong dissolution type (CBA type).

(2) The main diagenetic sequence was mechanical compaction-chlorite rim-early pore-filling calcite cementation-dissolution-authigenic kaolinite-quartz cementation-late calcite cementation.

(3) Differential diagenesis combination was mainly controlled by the petrological characteristics, microfacies, and fault. Low content of rock fragment and high content of detrital quartz were beneficial to the compaction resistance and cementation. The moderate content of pore-filling calcite was conducive to pore space protection and feldspar dissolution. The faults control dissolution and differential diagenesis combination by influencing the migration of acid fluids.

(4) CAC type was characterized by the high content of detrital quartz and calcite, which resulted in weak dissolution. The BBB type has experienced moderate compaction due to middle content of detrital quartz and calcite cement, which resulted in the moderate dissolution. The CBA type has more dissolved pores due to the moderate calcite cement and strong dissolution. The BBB and CBA type sandstones were in favour of reservoir development.

Data Availability

The data that support the conclusions of this study are available from text and the corresponding author upon reasonable request.
Conflicts of Interest

There are no conflicts of interest with respect to the results of this paper.

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