Diagenetic Control of Reservoir Performance and Its Implications for Reservoir Prediction in Jinci Sandstone of Upper Carboniferous in the Middle East Ordos Basin

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ABSTRACT: The Upper Carboniferous sandstone reservoir is a vital replacement area for natural gas exploration in Ordos Basin. In this study, 157 Jinci sandstone samples were selected to conduct a series of experiments and analyses. The reservoir material composition and pore structure analysis shows that the lithology of the reservoir is mainly quartz arenite, followed by sublithic arenite. The detrital particles are mainly quartz (69−97.5%), followed by rock fragments (0.1−24.5%), and the content of feldspar is less than 0.01%. The cement consists of siliceous material, clay minerals, and carbonate, with averages of 2.34, 5.96, and 1.81%, respectively. Three types of pore-throat structures (HPMI curve: types 1, 2, and 3) are identified in the Jinci sandstone reservoir, corresponding to different pore-throat radius distributions (RCP curves: types A, B, and C). The study of the factors affecting reservoir pore structure and its internal mechanism shows that the reservoir pore-throat combination, affecting the reservoir performance, is mainly controlled by deposit composition and the subsequent diagenetic modification. A higher rigid particle content and an appropriate amount of siliceous cementation (2−10%) would lead to resistance of the compaction, in favor of the preservation of primary intergranular pores. When the content of ductile particles is more than 3%, the original intergranular pores tend to be substantially reduced. The deposit composition of sandstone controls the preservation of residual intergranular pores by affecting the intensity of compaction and dissolution controlling the amount and type of cementation. Compared with dissolution-subjected quartz arenites, the sublithic arenites are characterized by a common occurrence of altered kaolinite and recrystallized illite, which would destroy the reservoir property. The early diagenetic carbonate cementation, as well as the strong siliceous cementation in “sedimentary quartz arenite”, are unfavorable to the formation of high-quality reservoirs. Then, on the basis of the characteristics of various diagenesis and their interaction and internal relationship, the diagenetic sequence and diagenetic-pore evolution patterns of different types of reservoirs were established. Finally, according to the lithological characteristics and the diagenetic-controlled pore-throat evolution patterns of different types of reservoirs, the reservoir quality in the study area was predicted.

1. INTRODUCTION

In recent years, with the continuous decline of conventional oil and gas production, unconventional resources have attracted much interest because of their huge reserves and exploration potential. The tight sandstone reservoir is of great significance to unconventional oil and gas systems. The continuous promotion of tight sandstone reservoir performance evaluation and “dessert” prediction is the key to tight sandstone gas exploration and utilization. The tight sandstone reservoir, with extremely low porosity and permeability (porosity <10%, permeability less than 0.1 mD), shows strong heterogeneity in the anisotropy of lithology, pore structure, and physical properties due to the diagenetic modification, among which, the micropore structure is of great significance for hydrocarbon filling, migration, and its exploitation, however, the pore system of the tight sandstone reservoir is tortuous with a small pore radius and poor connectivity, which makes the micropore structure difficult to accurately characterize. A large amount of research has been done on the pore type, pore-throat radius, pore structure of tight sandstone reservoirs, and interaction that the pore-throat structure posed on reservoir seepage capacity. However, the research on the pore-throat

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relationship and the diagenetic-controlled pore-throat evolution pattern of different pore-throat configuration types needs more attention.

The characteristics of reservoir pore structure, determining the reservoir quality, are strictly affected by the composition of the original sediments, as well as the modification of complex diagenesis during the postsedimentation. Therefore, research related to the impact of diagenetic alteration on reservoir quality is crucial for the efficient exploration, evaluation, and exploitation of tight reservoirs. Diagenesis mainly refers to various physical and chemical processes that occur after sediment deposition, including deep burial compaction (mechanical and chemical), mineral metasomatism, soluble components dissolution, and cementation. The original deposition composition and its structural characteristics, determined by original sedimentation, exert significant control on the types and intensity of diagenesis, resulting in the differential evolution of reservoir pore-throat structure.

Much work has been done to reveal the impact of different types of diagenesis on reservoir quality. It is considered that compaction caused by progressive burial is the main factor leading to the reduction of sandstone depositional porosities, which is controlled by the effective stress and mechanical properties of sediments. Various types of secondary minerals generated during the process of cementation can fill the pore throat of the reservoir and destroy the reservoir performance; meanwhile, a small amount of cement formed in the early diagenesis can improve the compaction resistance of the reservoir, which is of positive significance for the preservation of the primary intergranular pores. Dissolution may cause an increase in secondary porosity. It should be noted that the dissolution process will also be accompanied by the precipitation of cement such as clay minerals and quartz. Therefore, the research on the lithological characteristics integrating the genesis of the interaction and internal relationship and its impact on the pore evolution patterns of different pore-throat configuration reservoirs is essential. In addition, the Jinci sandstone is an important replacement area for natural gas exploration in Ordos Basin. However, relevant research on the Jinci sandstone reservoir in the study area is not rich enough. So, it is particularly urgent to carry out relevant work related to the influence of reservoir diagenesis on pore structure, clarify the influencing factors of diagenesis, and investigate the internal relationship and interaction between various diageneses based on a full understanding of the sedimentary background.

In this study, 157 Jinci sandstone samples of Upper Carboniferous in Ordos Basin were collected to conduct a detailed study on reservoir material composition, pore-throat structure, and diagenesis characteristics. On this basis, the relationship between pore types and pore structure characteristics is discussed, the influencing factors of reservoir diagenesis in the study area are clarified, and the internal relationship and interaction between various diageneses and their control mechanism on the reservoir pore structure are revealed. Then, the diagenetic sequence and diagenetic-pore evolution patterns of different types of reservoirs were established, which can provide a basis for reservoir quality prediction.

Figure 1. Structural location of the study area and distribution of the specific sampling wells of the Jinci sandstone in the present study. (a) Location of Ordos Basin. (b) Location of the study area. (c) Distribution of sedimentary facies in the study area.
2. GEOLOGICAL SETTING

The Ordos Basin, located in the west of the North China Plate (Figure 1a), is a multicycle sedimentary craton basin, as well as one of the most important petroliferous basins in China. The evolution of the current tectonic framework of the basin began in the middle of the Yanshanian movement and tended to be stable until the Himalayan movement. There are six secondary structural units in the basin (Figure 1b). The study area is close to the Western Shanxi Flexure Belt and located in the northeast of the Yishan slope. During the period of the Late Carboniferous, the regional structure showed a pattern of high in the north and low in the south, and transgression occurred in the south of the basin due to the tectonic movement of the plate. The study area is a tide transformed composite sedimentary system of a shallow water delta, wide sea lagoon, tidal flat, and carbonate tidal flat under the background of the confined epicontinental sea, and the deposits of subaqueous distributary channel, tidal bar, and tidal channel constitute the main sedimentary types of the Jincis sandstone (Figure 1c).

The Upper Carboniferous sediments in the research area show the integrated characteristics of four types of sedimentary systems: (1) weathered bauxite, (2) littoral and neritic clastic rocks, (3) tidal flat limestone, and (4) coastal swamp facies coal rock, carbonaceous mudstone, and ferroanluminate containing pyrite or siderite nodules and bands (Figure 2). The bottom of the Benxi Formation of Upper Carboniferous is mainly composed of iron and aluminum riched mudstone and shale and is called the Hutian member. The central Pangou member is mainly a set of the alternative sea and river facies environmental rock series composed of sandstone, shale, siltstone, and limestone, and coal seams are occasionally developed. Jinci sandstone is located at the bottom of the Jinci member, which belongs to the upper part of the Benxi Formation. In the Wushenqi and Shenmu-Qingjian areas, it is mainly subaqueous distributary channel deposits with large large-scale inclined beddings and trough cross-bedding formed in tide transformed shallow water delta environment.

2. SAMPLES AND METHODOLOGY

In this study, 157 Upper Carboniferous Jinci sandstone samples were collected from a total of 20 exploration wells for comprehensive research. First, a small part of each sandstone sample is taken for the preparation of cast thin sections (CTS). The CTS samples were made in China Petroleum Exploration and Development Research Institute, and then all thin sections were observed and identified by polarizing microscope technology to investigate the characteristics of mineral, pores, and reservoir morphology.

Then, 20 samples were selected from 157 samples to prepare samples with lengths of 0.5 and 4 cm, respectively. The 20 samples of 0.5 cm long were gold-coated and dried with FEI Quanta 250 for scanning electron microscopy (SEM) analysis. All these calculations were completed in the modern analysis and calculation center of the China University of mining and technology (CUMT). The other 20 4 cm long samples were used for the high-pressure mercury intrusion (HPMI) test.
intrusion pressure set was 9000 psi, corresponding to the pore-porosimeter at a rate of 0.00005 mL/min, and the maximum the samples were tested with an ASPE-730 mercury porosimeter (Autopore 9520). The upper limit was to the Chinese Standard SY/T5346-2005 with ACS Omega.

Finally, 10 samples were selected from the 20 samples to prepare 10 4 cm long samples for the rate-controlled porosimetry (RCP) test. According to the industrial standard, the samples were tested with an ASPE-730 mercury porosimeter at a rate of 0.00005 mL/min, and the maximum intrusion pressure set was 9000 psi, corresponding to the pore-throat radius of 0.004 μm.

4. RESULTS

4.1. Detrital Mineralogy. According to the petrographic identification and observation of 157 sandstone CTSs, the Jinci sandstones in the study area are mainly medium to coarse-grained (less fine-grained), medium to well-sorted, subangular to subrounded, linear contact to concavo-convex contact of detrital grains. According to the classification scheme proposed by folk, sandstone here is mainly quartz arenite, followed by sublithic arenite (Figure 3). The deposit compositions of reservoirs from different areas are shown in Table 1. It can be seen that the types of lithic fragments in different regions vary greatly. Compared with the Jiaxian-Ansai area, sublithic arenite quartz arenite in other regions has higher metamorphic lithic fragments content.

Detrital quartz (with content in the range 69–97.5%, an average of 85.94%) is the main detrital component of Jinci sandstone and is dominated by monocrystalline quartz (Figure 4a). In addition, there is a small amount of polycrystalline quartz, quartzite fragments, and chert (Figure 4b,c). Few detrital feldspars can be seen except for a small amount of acid plagioclase and striped feldspar from the source rock of the provenance area (Figure 4b), which can be the result of chemical weathering in the process of sedimentation and the dissolution of feldspar by acid fluid in coal-bearing strata during diagenesis.

The content of sandstone lithic fragments in the study area is 0.1–24.5% with an average of 3.33%, of which the volcanic lithic fragments (0.93%) are dominated by intermediate-acid eruptive lithic fragments. The metamorphic lithic fragments consist of both high metamorphic lithic fragments (average 1.07%) and lower metamorphic lithic fragments (phyllite 0.21%, slate 0.06%, schist, etc.). There is a small amount of sedimentary lithic fragments such as mudstone and siltstone fragments. In addition, the argillation and calcification of detrital particles can be seen, as they form a small amount of altered lithic fragments (average 0.46%). During the process of compaction, the ductile lithic fragments are prone to plastic deformation and concavo-convex contact with rigid particles or even occur in the form of a pseudomatrix, which can occupy most of the pore space (Figure 4c,e). In this study, they are collectively referred to as ductile fragments, including most lower metamorphic lithic fragments (such as schist, phyllite, and slate fragments) (Figure 4e), as well as mudstone fragments and mica (Figure 4b,f).

4.2. Cement. 4.2.1. Quartz. Statistics show that quartz cement exists in 94.63% of the tested Jinci sandstones, and its volume content is 0.1–14%, with an average of 2.34%, accounting for 17.2% and 14.7% of the total cement in quartz arenite and sublithic arenite, respectively (Figure 5). Quartz overgrowths (Figure 6a) and authigenic quartz (Figure 6g) that precipitated during late diagenesis of deep burial are the main forms of quartz cement. Some quartz cement exists via porous cementation, the point contact and short-line contact of detrital particles showing the characteristics of early diagenetic cementation (Figure 6b). Chemical compaction can provide siliceous material for the formation of quartz cement. In addition, the sources of quartz cement also include SiO2 precipitated during the transformation of clay minerals and silicon provided by volcanism during the sedimentary period.

4.2.2. Carbonate. The ferrocalcite cement in the sandstone reservoir often appears purplish red or purple (Figure 6d), which can be seen in 22.81% of the tested samples, with an average content of 1.81%. Calcite, red in the cast thin section (Figure 6c), can be found only in 10.07% of the total samples, with content between 0.1% and 12%. Both the calcite and the ferrocalcite fill the pore space heteromorphically (Figure 6c,d); in addition, a strong cementation structure with continuous crystal can also be formed in some of the samples (Figure 6e). Ankerite, with a percentage ranging between 0.1 and 4%, can be observed in 20.81% of examined samples. Most of them appear in the form of euhedral rhombohedral crystals; however, a small amount of them are microcrystalline aggregates, some of which show radial structures with dirty centers and pure edges, indicating two stages of crystallization (Figure 6e). There is little difference in the content of carbonate cement between quartz arenite and sublithic arenite (Figure 5). The dissolution of feldspar, as well as the transformation of clay minerals, can provide material sources for carbonate cement. The existence of a large amount of Fe3+ is evidence that the iron-bearing carbonate cement was mainly formed in the later diagenetic stage.

4.2.3. Clay. The authigenic clay cement in the study area mainly includes kaolinite, illite, and a small amount of mixed layer clay, with a percentage content of 0.1–16%. Kaolinite cement and illite cement can be seen in 93.96% and 92.62% of the examined samples, respectively, among which the quartz arenite is characterized by a high content of kaolinite cement. However, there is little difference in content between kaolinite and illite in sublithic arenite (Figure 5).

The content of kaolinite is 0.1–11%, with an average of 3.83%. According to its occurrence, kaolinite can be divided...
Table 1. Deposit Composition (Detrital Particles and Cement) of the Jincihe Sandstone Reservoir from Different Regions in the Study Area

| Location       | Sample | Depth (m) | Porosity (%) | Permeability (mD) | Detrital particles (%) | Lithic fragments | Carbonate cement | Clay cement | Cement (%) |
|----------------|--------|-----------|--------------|-------------------|------------------------|------------------|-----------------|-------------|------------|
|                |        |           |              |                    |                        | Quartz | Feldspar | VLF | ALF | Mica | Quartz | Calcite | Ferrocalcite | Ankerite | Kaolinite | Illite | Mixed layer clay |
| Hengshan-Zhidan| T12    | 2978.5    | 9.0          | 1.18              | 93.5                   | 0   | 0    | 0.1 | 1.5 | 0.1  | 2.5    | 0.1    | 0          | 0          | 1.5    | 0.5  | 0          |
|                | T81    | 3648.3    | 8.1          | 3.20              | 88.82                  | 4   | 0.58 | 0  | 0.5 | 0.2  | 2      | 0      | 0          | 0.2        | 3.5    | 0.1  | 0          |
|                | So215  | 3890.3    | 7.6          | 0.79              | 86.5                   | 3   | 0.5  | 0  | 1.7 | 0    | 2      | 0      | 1.5        | 0          | 4      | 0.8  | 0          |
|                | Tao37  | 3397.7    | 2.6          | 0.27              | 80.2                   | 3   | 1.7  | 0  | 2   |       | 3      | 0      | 0          | 0.1        | 0.5    | 2.5  | 0          |
|                | Tao39  | 3480.5    | 0.3          | 0.01              | 75.8                   | 5   | 15.5 | 0  | 0.5 | 0.5  | 1      | 0      | 0          | 0.2        | 0      | 1    | 0          |
|                | T3     | 3088.4    | 4.3          | 0.31              | 85.5                   | 3   | 1.5  | 0  | 0.6 | 0.1  | 2      | 0      | 3          | 2.1        | 0.2    | 1.8  | 0          |
|                | Shan398| 3863.3    | 4.9          | 0.29              | 95.8                   | 3   | 1    | 0  | 0.1 | 0    | 0      | 0      | 0          | 0          | 0      | 0    | 0          |
| Jiaxian-Ansai  | Mi128  | 2010.0    | 8.3          | 0.30              | 74.9                   | 10  | 0.5  | 0  | 3   | 0.1  | 3      | 0      | 0          | 1.8        | 2.5    | 4    | 0          |
|                | Mi174  | 2421.1    | 3.1          | 0.00              | 80.7                   | 0.2 | 2.6  | 0  | 0.2 | 0.1  | 4      | 0      | 0          | 0.1        | 3      | 0    | 0          |
|                | Mi119  | 3080.5    | 8.2          | 0.76              | 88.2                   | 0   | 3.2  | 0  | 0.1 | 0.5  | 0      | 0      | 4          | 0          | 3      | 0    | 0          |
|                | Qi20   | 2756.1    | 13.3         | 17.80             | 92.8                   | 0   | 0    | 0  | 0   | 0.8  | 0      | 0      | 0          | 0.1        | 5      | 1    | 0          |
|                | Mi138  | 2820.9    | 11.6         | 0.41              | 92.8                   | 0   | 0    | 0  | 0   | 0.1  | 3      | 0      | 0          | 2.2        | 0      | 2    | 0          |
|                | Mi72   | 2874.8    | 4.6          | 0.03              | 78.3                   | 0   | 0    | 0  | 0   | 0.1  | 0      | 0      | 0          | 0          | 0      | 1    | 0          |
|                | Qi24   | 2971.2    | 8.6          | 1.88              | 82.5                   | 0   | 0.5  | 0  | 0   | 4    | 0      | 0      | 1          | 0          | 5      | 0    | 0          |
| Shenmu         | Shen103| 2486.4    | 2.1          | 0.07              | 79.6                   | 0   | 9.5  | 1  | 0   | 5    | 0.2    | 0      | 0          | 0          | 0      | 0.2 | 0          |
|                | Shen62  | 2276.2    | 7.3          | 0.16              | 87.3                   | 0   | 0    | 0  | 0.2 | 0.5  | 5      | 0      | 0          | 3          | 1.5    | 3    | 0          |
| Wushenqi       | Tao25  | 3483.0    | 5.3          | 0.07              | 83.3                   | 7   | 1.5  | 0  | 0.3 | 0.5  | 5      | 0.2    | 0          | 1.5        | 0      | 0.5 | 0          |
|                | Zh15   | 3103.0    | 4.4          | 0.23              | 88.1                   | 2.5 | 0.8  | 0  | 0.8 | 0.3  | 4      | 0      | 2.1        | 0          | 1      | 0.2 | 0          |

*aVLF: volcanic lithic fragments; ALF: altered lithic fragments; MLF: metamorphic lithic fragments; SLF: sedimentary lithic fragments.*
into authigenically crystallized kaolinite and altered kaolinite. The authigenic kaolinite is mainly found in quartz arenite in the form of vermicular or “booklet” aggregates with crystals of a larger size (10 μm–20 μm) (Figure 6h), and the formation of authigenic kaolinite is closely related to the dissolution of feldspar aluminosilicate. Compared with authigenic kaolinite, altered kaolinite is smaller in single crystal size and shows poor automorphism (Figure 6f). It is dominantly found in tuffaceous sandstone and clean quartz arenite. The kaolinite cement can be formed at all stages of diagenesis. However, most of it was formed in the later stage.

Illite in the study area mainly includes altered illite and authigenic illite with the percentage content ranging from 0.1 to 15% and an average of 2.53%. Authigenic illite grows along the particle surface, with single crystals in a scaly shape and aggregates that are fibrous or hair-like (Figure 6i). It is generally developed in tuffaceous sandstone and clean quartz arenite. Altered illite is often colloidal with coarse grains, dense structure, and uniform aggregates. In addition, sericitization occurs on it (Figure 6f).
4.3. Pore Classification. The pore type and content distribution in sandstone with different lithologies are shown in Figure 7. Comparing the proportion of different types of pores in reservoirs with different lithologies, we can find that primary intergranular pores and secondary intergranular pores are more favorable within quartz arenite, while intragranular dissolved pores and intercrystalline micropores are more likely to be distributed in sublithic arenite.

The primary intergranular pore (PIEP) is the space preserved after sediment deposition. As a result of the modification of complex diagenesis, the intergranular pores that now exist are not intergranular pores in the original sedimentary period but transformed primary intergranular pores that present triangular, quadrilateral, or polygonal in shape (Figure 8a) and are mostly found in quartz arenite and some sublithic arenite with high rigid detrital particle content. Primary intergranular pores can be found among 42.29% of the tested samples with an average thin-section porosity of 2.06%.

Secondary intergranular pores (SIEPs) can be seen in 48.99% of the total samples. These are the space regenerated via dissolution of detrital grain margins or intergranular material (such as tephra and tuff material) and distributed between detrital particles in a harbor or irregular shape (Figure 8a,b) with an average porosity of 1.0%.

The detrital particles, such as feldspar and volcanic rock fragment particles in the sandstone, can be selectively dissolved, forming isolated and honeycomb-like dissolved pores in the grain interiors, and are called secondary intragranular pores (SIAP). Furthermore, mold pores formed by the complete dissolution of detrital particles can also be found (Figure 8c). All these dissolution phenomena can be observed in 47.65% of the tested samples, leading to a porosity
increase of 0.1–2.5% in thin sections, with an average of 0.45%.

Intercrystalline micropores (IEP) are common (Figure 8d,e,f) and can be observed in 89.93% of the sandstones, with average thin-section porosity of 2.51%. Intercrystalline micropores account for a high proportion in the sandstone (Figure 7) and thereby are an important reservoir space. Intercrystalline micropores in authigenic clay perform better than those in altered clay minerals in reservoir properties.

4.4. Pore-Throat Structure and Size Distribution.

4.4.1. Pore Structure Characteristics. Previous studies show that the threshold pressure and capillary pressure curve obtained from the HPMI test are closely related to the pore structure of the reservoir.33 In the present study, according to the integrated characteristics of the capillary pressure curve and threshold pressure ($P_d$), the sandstone reservoirs are divided into three types. The pore composition and pore structural parameters for each sample are listed in Table 2.

The samples of type 1 and type 2 reservoirs show the characteristics of a low $P_d$ value at 0.018 and 0.26 MPa, respectively, on average. The mercury intrusion curve of the type 1 reservoir shows a long flat section at the initial stage (Figure 9a). With the increase of $P_d$, the horizontal section of the type 2 reservoir intrusion curve narrows (Figure 9b). The type 3 reservoir, with maximum $P_d$ (average 6.1 MPa), displays the characteristics of being steep as a whole without a flat section (Figure 9c), indicating that from type 1 to type 3, the sorting of reservoir pore throat gets worse in turn, accompanied by the decrease of maximum mercury saturation ($S_{\text{max}}$). Meanwhile, the average and maximum pore-throat radii ($R_{\text{ave}}$ and $R_{\text{max}}$) decrease as well (Figure 10a). The $R_{\text{ave}}$ value for the type 1 reservoir ranges from 1.83 to 11.66 μm, with an average of 8.65 μm; however, the average values of $R_{\text{ave}}$ are smaller for the type 2 and type 3 reservoirs and are 0.71 and 0.38 μm, respectively. In addition, there is a crucial decrease in sample permeability with the decrease of the $R_{\text{ave}}$ value (Figure 10b).

4.4.2. Pore-Throat Size Distribution. The pore-throat structure parameters of 10 representative sandstone samples obtained from the RCP test are shown in Table 2. In addition,
| Location       | Well name | Depth (m) | Total PIEP | SIEP | SIAP | IEP | HPMI types | P ($\text{MPa}$) | $S_{\text{max}}$ ($\text{MPa}$) | $S_{\text{r}}$ ($\text{MPa}$) | $R_{\text{ave}}$ ($\mu\text{m}$) | $R_{\text{max}}$ ($\mu\text{m}$) | RCP types | $R_{\text{ave}}$ ($\mu\text{m}$) | $R_{\text{ave}}$ ($\mu\text{m}$) | $\eta_{\text{ave}}$ | $S_{\text{f}}$ (%) | $S_{\text{p}}$ (%) | $S_{\text{t}}$ (%) |
|----------------|-----------|-----------|------------|------|------|-----|------------|----------------|----------------|----------------|----------------|----------------|------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Jiaxian-Ansai  | Mi128     | 2010      | 4.25       | 0.5  | 1    | 1.5 | 1.25       | 2              | 0.5            | 79.60          | 49.67          | 0.34           | 1.47          | -           | -             | -             | -             | -             | -             |
|                | Mi174     | 2421.1    | 0.5        | 0    | 0    | 0   | 0.5        | 3              | 5.0            | 7.10           | 1.68           | 0.01           | 0.01          | -           | -             | -             | -             | -             | -             |
|                | Mi119     | 3080.49   | 0.2        | 0    | 0    | 0   | 0.1        | 2              | 0.15           | 77.10          | 64.38          | 1.09           | 4.90          | B           | 213.24        | 1.25          | 202.90        | -             | 35.24         | 35.76         |
|                | Qz20      | 2756.13   | 11.6       | 5    | 3    | 0.1 | 3.5        | 1              | 0.01           | 93.00          | 81.00          | 11.66          | 73.50         | A           | 307.14        | 8.29          | 43.88         | 74.37         | 30.29         | 44.08         |
|                | Mi138     | 2820.94   | 3.1        | 1    | 0.7 | 0   | 1.5        | 3              | 0.3            | 62.80          | 55.58          | 0.71           | 2.45          | C           | 205.55        | 0.66          | 327.86        | 37.25         | 21.07         | 16.18         |
|                | Mi72      | 2874.8    | 0.1        | 0    | 0    | 0   | 0.1        | 3              | 1.5            | 20.10          | 11.40          | 0.17           | 0.49          | -           | -             | -             | -             | -             | -             |
|                | Qz34      | 2971.22   | 2.9        | 1    | 0.7 | 0   | 1.5        | 1              | 0.1            | 79.70          | 61.69          | 11.25          | 73.50         | A           | 189.00        | 1.39          | 164.00        | 84.13         | 59.18         | 24.95         |
| Hengshan-      | Shen90    | 2052.55   | 3.8        | 1    | 0.3 | 0   | 1.5        | 1.5            | 0.01           | 75.80          | 47.22          | 9.54           | 73.50         | A           | 188.00        | 1.63          | 156.00        | 82.09         | 52.61         | 29.49         |
| Zhidan        | T12       | 2978.48   | 1.9        | 0.1 | 0.4 | 0.4 | 0.4        | 1              | 0.05           | 68.00          | 61.54          | 11.25          | 73.50         | C           | 195.00        | 3.01          | 138.00        | 87.48         | 37.17         | 39.25         |
|                | T81       | 3648.32   | 2.3        | 0.1 | 0.2 | 0.5 | 1.5        | 1              | 0.01           | 84.00          | 68.80          | 7.99           | 73.50         | A           | 175.00        | 3.01          | 138.00        | 87.48         | 37.17         | 39.25         |
|                | Su215     | 3890.34   | 2.3        | 0    | 0   | 0   | 0.5        | 2              | 0.2            | 76.50          | 47.74          | 0.69           | 3.67          | B           | 194.04        | 1.47          | 161.75        | 79.48         | 40.25         | 39.23         |
|                | Tao37     | 3397.72   | 0.7        | 0    | 0.1 | 0.2 | 0.4        | 3              | 0.2            | 81.80          | 55.38          | 0.48           | 3.68          | -           | -             | -             | -             | -             | -             |
|                | Tao39     | 3480.45   | 0.7        | 0.1 | 0.1 | 0.2 | 0.3        | 3              | 0.2            | 32.00          | 2.50           | 0.68           | 3.68          | -           | -             | -             | -             | -             | -             |
|                | T3        | 3088.42   | 0.4        | 0    | 0    | 0   | 0.1        | 0.3            | 0.3            | 85.20          | 34.68          | 0.31           | 2.45          | C           | 157.00        | 0.48          | 308.00        | 58.44         | 20.91         | 37.54         |
|                | Shan398   | 3863.31   | 0.3        | 0    | 0    | 0   | 0.3        | 3              | 0.3            | 88.40          | 69.66          | 0.42           | 2.45          | C           | 154.00        | 0.38          | 366.00        | 48.11         | 17.43         | 30.68         |
|                | Shan468   | 3181.42   | 1.3        | 0    | 0.3 | 0.5 | 0.5        | 2              | 0.2            | 96.80          | 53.82          | 0.64           | 3.68          | -           | -             | -             | -             | -             | -             |
| Shenmu         | Shen103   | 2486.4    | 3.2        | 1    | 0.7 | 0   | 1.5        | 3              | 0.3            | 67.00          | 41.67          | 0.32           | 2.45          | C           | 155.00        | 0.43          | 277.00        | 30.37         | 17.29         | 13.08         |
|                | Shen62    | 2276.19   | 4.6        | 0.1 | 1   | 1.5 | 2          | 3              | 0.3            | 84.50          | 51.46          | 0.48           | 2.45          | C           | 154.00        | 0.38          | 366.00        | 48.11         | 17.43         | 30.68         |
| Wushenqi       | Tao25     | 3482.96   | 0.7        | 0    | 0    | 0.2 | 0.5        | 3              | 1.5            | 85.00          | 48.28          | 0.12           | 0.49          | -           | -             | -             | -             | -             | -             |
|                | Zh15      | 3102.97   | 0.3        | 0    | 0    | 0   | 0.1        | 2              | 0.2            | 68.00          | 42.50          | 1.20           | 3.68          | -           | -             | -             | -             | -             | -             |
the distributions of the pore radius ($R_p$), throat radius ($R_t$), and pore-throat radius ratio ($\eta$) of sandstone samples are obtained as well (Figure 11). It can be seen that the distributions of the pore radius of different sandstone samples are similar, with roughly the same peak center. However, the distributions of the throat radius and pore-throat radius ratio are quite different (Figure 11a,c,e), indicating that the throat radius plays an important role in controlling the reservoir permeability, which is consistent with the previous studies.23

On this basis, according to the throat radius distribution, the reservoir is divided into three types: (A) multimodal-low kurtosis (Figure 11a); (B) unimodal-low kurtosis (Figure 11c); and (C) unimodal-high kurtosis (Figure 11e). From type A to type C, the average pore radius ($R_{p,ave}$) decreases in turn; however, the pore-throat radius ratio increases gradually, indicating a sharp decrease in the throat radius, which is consistent with the experimental results that the average throat radii ($R_{t,ave}$) of type A and type B reservoirs are larger, with averages of 3.24 and 1.36 $\mu$m, respectively. However, for the type C reservoir, there is a sharp reduction in the average throat radius to 0.49 $\mu$m.

The mercury intrusion curve of the three types of reservoirs based on the RCP test is shown in Figure 12. From reservoir type A to reservoir type C, the $P_d$ value increases, and the final mercury saturation ($S_f$) decreases; meanwhile, with the increased displacement pressure, the pore intrusion curves get steeper. In addition, the total intrusion curve can be subdivided into a pore mercury intrusion dominated segment and throat mercury intrusion dominated segment according to the contribution of pore and throat to total mercury saturation.
Among these three types of reservoirs, the total mercury saturations of type A and type B reservoirs are both dominated by pores intrusion and are 44.08% and 37.75%, respectively (Figure 12a,b); the type C reservoir has a long throat mercury intrusion leading segment (Figure 12c), and the throat mercury saturation \( (S_t) \) is greater than the pore mercury saturation \( (S_p) \) (19.18% in the pores and 24.37% in the throat).

### 4.5. Physical Properties of the Sandstone Reservoir.

The porosities of sandstone samples in the study area are 0.56–21.73%, averaged to 6.52%, and the permeability ranges from 0.001 mD to 21.78 mD, averaged to 0.4612 mD. Meanwhile, the thin-section porosities obtained from petrographic analyses are in the range 0–15.2%, with an average of 3.83%. Except for a few samples, the overall seepage capacity of the samples in the present study is poor, showing the characteristics of a typical tight sandstone reservoir. As is shown in Figure 13, the porosity and permeability obtained by these different methods both show a significant positive correlation, and the correlation between the porosity and the permeability measured by the plunger sample \( (R^2 = 0.5256) \) is stronger than that from CTS. It is mainly because the micropores exist in tight sandstone reservoirs, which can contribute to the reservoir porosity and permeability, but they are difficult to identify and accurately quantify during petrological analyses, which can also be confirmed by the phenomenon that the thin-section porosity is smaller than the porosity measured with plunger samples.

### 5. DISCUSSION

#### 5.1. Diagenetic Controls on Reservoir Performance.

After sediment deposition, the modification of diagenesis on reservoir cement and pore-throat characteristics played the leading role on controlling reservoir physical properties and
heterogeneity. During the diagenesis process, compaction and cementation may cause a significant reduction in reservoir porosity. On the contrary, the dissolution of skeleton particles and intergranular materials will improve the reservoir performance to a certain extent.\(^\text{34,35}\) The difference between reservoir heterogeneity and physical properties in the study area is closely related to reservoir material composition, indicating that the influence of material composition on diagenesis is the key to reservoir performance.

5.1.1. Compaction. Compaction can cause significant decreases in intergranular volumes and geometric shape change in the pore-throat system, resulting in release of diagenetic fluid from the pore-throat system, so that the soluble substances in sandstone are mainly transformed into altered clay under high pressure and temperature, and thereby greatly restricts the formation of secondary pores. Moreover, the poor flow capacity caused by compaction may show a negative impact on the progress of dissolution, thus affecting the reservoir performance of sandstone. Previous studies have demonstrated that the initial porosity of well-sorted sandstone refers to 40\%.\(^\text{36}\) On this basis, porosity damage caused by compaction and cementation of the sandstone samples is investigated as Figure 14 shows, which indicates that compaction is a fatal factor for porosity loss of sandstone reservoirs. In addition, the porosity reduction resulting from the compaction of sublithic arenite is more than that of quartz arenite. Various factors affects the rate and intensity of compaction, including deposit composition, rock physical properties, as well as many external influence factors (such as burial rate, sand
The sublithic arenite with high content of ductile components (such as mica, soft rock debris, clay matrix, etc.) in the study area is significantly affected by compaction, and the detrital particles are mostly in concavo-convex contact (Figure 4c), with stronger loss of primary pores (Figure 7), while the quartz arenite with fewer ductile components retain more primary pores (Figure 7, Figure 8a). This proves that the material composition of sandstone in the study area is the key factor controlling the intensity of compaction.

The primary intergranular pores tend to disappear in sandstone with ductile particle content greater than 3% (Figure 15a), indicating that the deformation of ductile grains caused by compaction controls the loss of primary intergranular pores. Previous research has demonstrated the higher the content of sandstone ductile material, the more thorough the compaction, resulting in greater porosity loss. On the contrary, rigid particles show the poor ability of plastic deformation and can resist compaction, which is conducive for primary intergranular pores to be preserved. Therefore, compared with sublithic arenite, the quartz arenite with fewer ductile components and high content of rigid particles (Figure 16a,b) retains more primary intergranular pores.

Previous studies proposed that cementation in the early diagenetic stage can resist compaction and is beneficial to the preservation of original pores. In the present study, the primary pores are mostly distributed in sandstone reservoirs in which the quartz cement varies in the range of 2–10% (Figure 15b). Quartz cement and rigid particles can enhance the compaction resistance ability of sandstone, thereby resulting in relatively higher residual intergranular pore volume. However, when quartz cement is more than 10%, it will occupy the original pore volume, causing the reduction of the original intergranular pore volume. The reservoirs less than 2% in quartz cement content are mostly sublithic arenite, for which the intensity of compaction is dominated by ductile grains.

5.1.2. Cementation. Multiple cementations (siliceous, clay minerals, carbonate, etc.) occurred on the sandstone reservoir in the study area, among which the quartz and kaolinite cementation are mostly found in quartz arenite (Figure 16c), while illite-dominated clay cement and carbonate cement are the main cementation types in sublithic arenite (Figure 16d). This shows that the material composition of the sandstone reservoir controls the type and intensity of cementation and thereby affects the performance of the sandstone reservoir.

Quartz cement in the study area mainly occurs as quartz overgrowth (Figure 6a) and a small amount of authigenic quartz particles (Figure 6g). Diversity of sources exists for quartz cement, including alteration and dissolution of tephra and detrital feldspar, in situ pressure solution, and transformation of clay minerals, among which, the silica from silicate dissolution is the main source of quartz cement. The primary intergranular pores retained in quartz arenite provide a fluid channel for the dissolution of volcanic materials and space for quartz precipitation in the early diagenetic stage and thus result in the relatively developed quartz overgrowth in quartz arenite (Figure 16c). However, since pore fluid in sublithic arenite is mostly discharged under the early compaction, the silicate and volcanic materials in the sandstone were mainly transformed into altered clay during the deep burial period. Therefore, less quartz overgrowth and only a small amount of authigenic quartz particles coexisting with clay minerals can be found in sublithic arenite. For quartz arenite, the more quartz cement, the worse the reservoir physical properties (Figure 17a). However, for sublithic arenite, the content of quartz cement is positively correlated with the intensity of compaction. The sublithic arenite with high content of ductile components (such as mica, soft rock debris, clay matrix, etc.) in the study area is significantly affected by compaction, and the detrital particles are mostly in concavo-convex contact (Figure 4c), with stronger loss of primary pores (Figure 7), while the quartz arenite with fewer ductile components retain more primary pores (Figure 7, Figure 8a). This proves that the material composition of sandstone in the study area is the key factor controlling the intensity of compaction.

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![](https://i.imgur.com/39709.png)

**Figure 14.** Plotting of porosity damage caused by compaction and cementation of the Jinci sandstone samples.

![](https://i.imgur.com/39709.png)

**Figure 15.** Box plots diagram of primary intergranular pore content versus the content of (a) reservoir ductile particles and (b) quartz cement.
Figure 16. Box diagram of composition and content distribution of detrital particles (a, b) and cement (c,d) in sandstones with different lithologies.

Figure 17. Scatter diagram of the reservoir permeability of sandstones with different lithologies versus (a) quartz cement content, (b) kaolinite cement content, (c) illite cement content, and (d) carbonate cement content.
permeability in the range of less than 5% (Figure 17a). This means that a small amount of quartz cement in ductile fragment-rich sandstone is of positive significance to enhance its compaction resistance ability.

Previous studies have demonstrated that the authigenic kaolinite is formed in an acidic environment with low $K^+$ content. The Upper Paleozoic coal-bearing strata in Ordos Basin is rich in acidic media; moreover, it contains detrital feldspars and abundant volcanic materials; all these together provide favorable conditions for the formation of kaolinite. The primary intergranular pores generally preserved in quartz arenite are necessary for the fluid exchange and complete dissolution of silicate minerals, which are conducive to the precipitation of authigenic kaolinite. However, there are a few primary intergranular pores in sublithic arenite; in this case, the matrix and feldspar particles are supposed to be altered by adsorbing water to form altered kaolinite. In quartz arenite, no significant correlation exists between the kaolinite cement content and the sandstone permeability (Figure 17b), since precipitated kaolinite can form a large number of intergranular micropores while reducing the macropore volume. However, for sublithic arenite, at the stage of kaolinite cement less than 4%, it shows a positive correlation with reservoir permeability, and when it is greater than 4%, the reservoir permeability decreases significantly (Figure 17b). On one hand, a small amount of kaolinite can provide intercrystalline micropores; moreover, it is also evidence of a certain degree of dissolution in the sandstone. On the other hand, the higher

Figure 18. Box diagram of porosity (obtained from CTS) of different types of pores in quartz arenite and sublithic arenite in Jinci sandstone.

Figure 19. Scatter diagram of the reservoir permeability versus the CTS porosity of (a) primary intergranular pores, (b) secondary intergranular pores, (c) secondary intragranular pores, and (d) intercrystalline micropores in Jinci sandstone.
kaolinite content represents the development of altered kaolinite with fewer intercrystalline micropores. Illite is also an important clay mineral in sandstone, including heterobasic illite, authigenic illite, and illite altered from volcanic ash. Altered illite is mostly found in sublithic arenite with more ductile particles; for these reservoirs, compaction instead of cementation plays a more dominant role in reservoir performance.

Authigenic illite mostly comes from the dissolution of feldspar and the transformation of kaolinite. During the diagenetic stage, if the K+ provided by K-feldspar cannot be taken away or the diagenetic fluid is rich in K+, it is more likely to form authigenic illite. The appearance of pore-attaching and pore-bridging authigenic illite leads to a significant reduction in reservoir performance (Figure 17c).

Carbonate cement can poikilitically cement detrital particles and fill large intergranular spaces, which has posed significant impact on reservoir performance and pore structure heterogeneity. Carbonate cementation precipitation can occur during the whole diagenesis period. The thermal evolution of organic matter, feldspar dissolution, as well as transformation of clay can provide materials required for carbonate cement precipitation. With the increase of carbonate cement content, the permeability of the reservoir decreases significantly (Figure 17d). Local reservoirs in the study area are affected by marine fluids, forming a lot of dolomite cement in the early stage of diagenesis, which destroys the reservoir performance.

5.1.3. Dissolution. Secondary dissolved pores resulting from dissolution are significant reservoir spaces for sandstone reservoirs. The petrographic analyses show that the porosity contributed by secondary pores of the reservoir in the study area is 0.01–6.1%, with an average of 0.71%, accounting for 27.3% of the total porosity. The secondary

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### Table 1. Diagenetic Processes and Their Effects

| Process                  | Early Diagenesis A | Early Diagenesis B | Middle Diagenesis A | Middle Diagenesis B |
|--------------------------|--------------------|--------------------|---------------------|---------------------|
| Siderite cementation     |                    |                    |                     |                     |
| Calcite cementation      |                    |                    |                     |                     |
| Compaction               |                    |                    |                     |                     |
| Dissolution              |                    |                    |                     |                     |
| Quartz cementation       |                    |                    |                     |                     |
| Ferrocalcite cementation |                    |                    |                     |                     |
| Ferrodolomite cementation|                    |                    |                     |                     |
| Kaolinite cementation    |                    |                    |                     |                     |
| Illite cementation       |                    |                    |                     |                     |

### Figure 20. Diagenesis-controlled pore evolution pattern of the Jinci sandstone reservoirs.

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dissolved pores in quartz arenites of the present study are dominated by intergranular dissolved pores; however, in sublithic arenite, it is mostly intragranular dissolved pores (Figure 18).

The relationship analysis between thin-section porosity of different types of pores and reservoir permeability shows that the porosity of primary intergranular pores and secondary intergranular pores is positively correlated with reservoir permeability (Figure 19a,b); however, there is no obvious correlation between intragranular dissolved pore porosity and reservoir permeability (Figure 19c). It is because the reservoirs, with intergranular pores developed, are mainly quartz arenite, while intragranular dissolved pores mostly exist in the sublithic arenites (Figure 18). Previous studies have shown that the migration channel of acid fluid (fracture, lithologic interface, pore-throat system) is the main factor affecting the dissolution intensity.\(^6\) Quartz arenite in the study area tends to preserve more intergranular pores that are beneficial to the fluid exchange, which can promote the dissolution,\(^3,6,3\) resulting in plenty of secondary dissolved pores in quartz arenite to greatly improve the reservoir permeability; however, for sublithic arenite, the diagenetic fluid in the sandstone is easy to discharge during early compaction, resulting in less dissolution of the reservoir; what’s more, the small amount of dissolved product from the soluble component is difficult to transfer away,\(^6\) and there is a trend to precipitate nearby to form the clay and quartz cement,\(^6\) which would fill the dissolved pores formed in the early stage,\(^5\) thereby resulting in the limited improvement of reservoir performance by dissolution. In addition, in the sublithic arenite reservoir without strong dissolution, the tuffaceous tends to be dehydrated under high temperature and pressure and would transform into clay minerals such as smectite and illite, which enhances the compaction and result in the reduction of the reservoir performance (Figure 19d).

Therefore, dissolution can significantly improve the physical properties of primary intergranular pore developed reservoirs dominated by quartz arenites; however, for the reservoir dominated by sublithic arenite with fewer primary intergranular pores, although some dissolution pores can be formed through dissolution, it shows a limited impact on reservoir physical properties.

5.2. Diagenetic-Pore Evolution of Different Types of Reservoirs. Porosity and permeability are direct indicators for...
reservoir performance evaluation, and their influencing factors vary, however, all of them control the sandstone reservoir performance by affecting the reservoir pore structure. According to HPMI and CRP tests, three types of pore-throat structures are classified among Jinci sandstone reservoirs (Figure 9), corresponding to different pore-throat radius distributions (Figure 12). Sandstone, with type 1 pore-throat structure, is mainly quartz arenite with various pore types and a large throat radius (average 2 μm), and therefore shows the best reservoir performance. The intercrystalline micropores are mostly distributed in the type 3 pore-throat structure sandstones. This type of reservoir has the worst physical properties with a tube bundle throat and small throat radius (less than 1.3 μm). The physical properties of the sandstone reservoir with type 2 pore-throat structure are between type 1 and type 3, which is dominated by the secondary dissolved pores.

According to the diagenesis characteristics of Jinci sandstone, especially the relative sequence of various cementation, the diagenetic evolution sequence of the sandstone reservoir is established, and the diagenetic-pore evolution patterns for different types of reservoirs is analyzed (Figure 20). It can be seen that the early compaction and cementation intensities of sandstones with different deposit compositions vary, which affects the distribution of residual primary intergranular pores and further affects the intensity of dissolution and cementation, resulting in different pore-throat structures and physical properties of the reservoir (Figure 11, Figure 20).

5.3. Implications for Reservoir Performance Prediction. The diagenetic-pore evolution of sandstone, determined by the original deposit composition, affects the pore structure and pore-throat radius distribution of the reservoir and thereby controls the reservoir performance. Therefore, based on the deposit composition and diagenetic-pore evolution pattern of sandstone in the study area, the exploration potential of the Jinci sandstone reservoir in the study area can be predicted.

The underwater distributary channel sandstones and tidal bar sandstones in the Jiaxian-Ansai area of the study area are mainly quartz arenite characterized by the high content of quartz detrital particles, low content of ductile components, and almost no clay matrix. The coexistence of multiple types of pores in the reservoir results in a wide distribution of pore-throat radius. The reservoir follows the type 1 pore structure reservoir diagenetic-pore evolution pattern and shows high reservoir performance, which is often proved to be gas bearing (Figure 21a). Therefore, this area is considered to be a high-quality reservoir area.

Sandstone reservoirs in the Shenmu and Wushenqi area, especially the distributary channel edge sandstone, are dominated by sublithic arenite with relatively high content of rock fragments and ductile components such as the clay matrix. These reservoirs are dominated by intergranular pores and show a higher illite content (Figure 21c). The type 3 pore structure reservoir diagenetic-pore evolution pattern greatly destroyed the reservoir performance. The reservoirs here are mainly dry layers, and this area therefore is referred to as a poor-quality reservoir area.

The Hengshan-Zhidan area is dominated by quartz arenite. The reservoir pore evolution is mainly the type 2 pattern; however, the quartz and calcareous cements in local regional reservoirs can occupy the reservoir pores, making the reservoir pore space be dominated by intragranular dissolved pores. The physical properties of this kind of reservoir are relatively poor, and most of them are poor gas layers. Therefore, this area is less favorable.

6. CONCLUSION

The following points are made as our results:

1. Jinci sandstone in the present study is mainly quartz arenite, followed by sublithic arenite. The detrital particles are mainly quartz (69−97.5%), followed by rock fragments (0.1−24.5%), and the content of feldspar is less than 0.01%. The cement is mainly siliceous material, clay minerals, and carbonate cementation, with averages of 2.34%, 5.96%, and 1.81%, respectively. Three types of pore-throat structures (HPMI curve: types 1, 2, and 3) are identified in sandstone, corresponding to different pore-throat radius distributions (RCP curve: types A, B, and C).

2. The deposit composition of sandstone controls the preservation of the primary intergranular pores by affecting the intensity of compaction, further determining the intensity of dissolution, and controlling the intensity and type of cementation. Higher rigid particle content and an appropriate amount of siliceous cementation (2−10%) in sublithic arenite are favorable for the preservation of primary intergranular pores. When the content of ductile particles is more than 2%, the primary intergranular pores tend to disappear. Compared with quartz arenite with substantial dissolution, the high plastic sublithic arenite is characterized by relatively poor reservoir performance for the higher content of altered kaolinite and recrystallized illite. Dissolution shows a limited impact in controlling the permeability of the reservoir dominated by sublithic arenite with fewer primary intergranular pores.

3. The reservoir pore-throat configuration type is mainly controlled by the sandstone deposit composition and diagenetic alteration. According to the lithological and diagenetic characteristics of different pore-throat configuration reservoirs, the diagenetic-pore evolution patterns of different types of reservoirs are established.

4. The sandstone reservoir in the Jiaxian-Ansai area follows the diagenetic-pore evolution patterns of the type 1 and type 2 pore structure reservoirs, where the type 1 is considered to be the favorable area. The type 3 diagenetic-pore evolution pattern is more inclined to appear in the Shenmu and Wushenqi areas where sublithic arenite is widely distributed. This area is considered as the type III favorable area.

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Notes
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