Evaluation Methods of Profitable Tight Oil Reservoir of Lacustrine Coquina: A Case Study of Da'anzhai Member of Jurassic in the Sichuan Basin

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Abstract: Based on core observation, cast and fluorescent thin sections, FESEM and ESEM, coquina in Da'anzhai Member of Jurassic in Sichuan Basin were examined systematically. Together with production data and logging evaluation, a method for lacustrine coquina evaluation based on geological theory was established up. In the article, two aspects of the study were elaborated, characteristics of favorable reservoirs, and a “five-step” evaluation method for favorable coquina reservoir. According to the correlation between porosity and production data, porosity is not effective in finding high quality coquina reservoir of this area. Whereas micro research of reservoir samples from a high productivity well revealed that sparry coquina is the best lithofacies, with the most developed micro storage space of various kinds. After the favorable reservoir was sorted out, a five-step method evaluating the coquina reservoir was worked out. Correlation of GR value and rock types suggests that GR<30 API is an effective evaluation parameter in identifying profitable reservoir lithofacies. Meanwhile, the combination of profitable reservoir rock thickness and production data revealed that the reservoirs with the highest potentiality are those with thickness of 3–18 m. Fractures are more developed in faults, folds and structural noses in the study area. Organic acid is discharged massively before the peak of hydrocarbon generation, leading to the formation of dissolution pores in the reservoir. The evaluation of organic acid was made by using the source rock indexes. After evaluating the four factors, and compiling their distribution maps, the maps were overlapped to predict favorable reservoir zones, and 7 first class and 9 second class favorable zones of coquina were picked out.

Key words: coquina, lithofacies, logging evaluation, favorable areas, Sichuan Basin

1 Introduction

Lacustrine carbonate rocks are widely distributed across the world (Zeng et al., 2012; Bohacs et al., 2013; Gareth and Xiao, 2013; Muniz and Bosence, 2018; Cao et al., 2019), and are common oil and gas reservoirs (Peng, 2011; Tang et al., 2015; Bao et al., 2015; Song et al., 2017; Cao et al., 2017 Wang et al., 2019). Coquina is an unique lacustrine carbonate rock, mainly composed of shells, can also be profitable reservoir rock. Such as the pre-Salt coquinas of Brazil and West Africa (Thompson et al., 2015), especially in Campos and Santos basins (Fick et al., 2018). The Da'anzhai Member of the Jurassic in the Sichuan Basin is also mainly composed of shells. And it has gone through more than half a century of oil and gas exploration and development. A lot of work has been done to analyze the characteristics of this reservoir. Xu Shuanghui et al. believed that the reservoir space of Da 1 Member was dominated by intragranular dissolved pores and fractures, while that of Da 13 Member was dominated by intragranular dissolved pores (Xu et al., 2013). Zheng Rongcai et al. established the geological model of reservoir space in Da'anzhai Member, and believed that the greatest contribution to Da'anzhai Member was all kinds of fractures, and dissolved fractures, dissolved pores and vugs formed along them, followed by intergranular pores. Although small in size, dissolved micro-pores and micro-fractures are large in number, their contribution cannot be ignored (Zheng et al., 2013; Zheng et al., 2016). According to the research results and different classification system, other researchers classified the reservoir space including fractures and pores in the coquina of Da'anzhai Member (Huang et al., 2010; Chen et al., 2013; Zhang and Peng, 2016; Tian et al., 2017). These works have deepened the understanding of the
characteristics of tight reservoirs in Da’anzhai Member. However, it is also noted that the previous studies mostly analyzed the tight reservoirs in Da’anzhai Member from the perspective of mechanism and theory, and no operable evaluation method has been worked out to translate the theoretical knowledge into practical use. Since the coquinas reservoirs always present many production-development challenges due to their heterogeneous nature (Corbett et al., 2017), it is necessary to determine where the profitable coquinas reservoirs developed. In order to solve this problem, the authors have worked out a favorable reservoir evaluation method of lacustrine coquina based on geological knowledge, the interpretation of a large number of production data and the study of reservoir micro-characteristics and logging evaluation.

2 Geological Background

The Sichuan Basin is characterized by "one uplift surrounded by three depressions" in tectonic framework. The central part of the Sichuan Basin is a paleouplift with gentle structure (Fig. 1). During the Jurassic period, the basin was a depression-type continental lake basin, while in the sedimentary period of the Da’anzhai Member, the basin was in the main transgression period, with an area three times as large as that of the present basin (Deng, 1992). Due to the insufficient supply of source material from the surrounding mountains, the basin was in hungry deposition, and the delta deposits were small in scale and all located at the edge of the basin. In the central part of the basin, the sedimentary facies were mainly semi-deep lacustrine facies-shallow lacustrine facies-shore lacustrine facies, and the rocks deposited were largely unequal thick interbeds of dark gray, grey-black mudstone and lacustrine coquina. The coquina mainly formed in a saline lake basin (Pan et al., 2015), is distributed in the upper Da 1 and lower Da 3 sub-members, which are separated by thick dark mudstone shale of Da1 sub-member (Fig. 1). Petrologically, the coquinas are mainly composed of biological shells and their detritus, with the content ranging from 50% to 98%, which are mainly lamellibranch shell fragments, with a small number of ostracods, pleopods and fish bone fragments (Wang, 1983). In terms of sedimentary environment, the coquina was mainly formed in the shell beach in shallow lacustrine facies (Chen et al, 2019), and it is the main reservoir rock (Yang et al., 2016). In the strong hydrodynamic beach core occurs pure coquina, and with the decrease of hydrodynamic force, the content of fillings increases in the flank of the coquina beach. Coquinas with different shale (crystal) contents are differences in micro-structure. In terms of macro-distribution, the single shell beach is usually lenticular shape, with thick pure coquina at the core and shale content increasing towards both sides. However, multi-stages of shell beaches often overlap with each other, forming coquina reservoir continuous in lateral distribution in Da 1 and Da 3 sub-members. On the plane, the coquina appears in large rings around the hydrocarbon source area in the central basin (Zheng, 1998).

3 Samples and Methods

In this work, samples were used for different research purposes with different methods. The samples can be classified into 3 parts. Samples of the first part were used to study the porosity characteristics of favorable
reservoirs. In this study, samples from 17 wells with high-yield and low-yield were selected to test the porosities to find out the relationship between the porosity and produced fluids (including oil, gas and water). These 17 wells were distributed across the study area (Fig.1).

Samples of the second part were used to research the lithofacies characteristics of favorable reservoirs. These samples were acquired from a high-yield coring well (Well J), and were analyzed by combining the oil-bearing observation techniques such as fluorescent thin section and environmental scanning electron microscope. Since the production wells in the study area all produce both oil and gas, in order to take both into account, natural gas was converted into oil and gas equivalent, and the sum of crude oil production in "ton" was regarded as the output of a single well. Statistics of oil wells in the study area show that only 22.5% of the wells have cumulative oil and gas equivalent of more than 10,000 tons, but their production combined account for 84.4% of the total cumulative production in the study area. Well J, a high-yield well in J oilfield, cored in the whole Da’anzhai Member was selected. In 2009, it was nearly shut down, with a cumulative crude oil production of over 2.0×10^4 tons, a cumulative gas production of over 2000.0×10^3 m³. The cumulative thickness of Da’an’zhai Member in Well J is 62.28 m. In lithological assemblage, the cumulative thickness of coquina in its Da’an’zhai Member is 39.27 m, mainly in Da1 and Da3 sub-members, the shale in it is 17.57 m thick and mainly in Da1 sub-member, and the remaining 5.44m is argillaceous siltstone and silty mudstone (Fig. 2). Through systematic core description, a total of 86 fine changes of macrolithofacies were recorded. After merging similar macrolithofacies, 29 reservoir samples with different macrolithofacies characteristics were collected to make thin sections for fine microscopic analysis.

Samples of the third part were used to find out evaluation parameters of the favorable reservoirs. Forty such reservoir samples were collected from 8 coring wells in the study area for rock type identification, and the GR curve values of all the samples were calibrated.

4 Results and Discussion

4.1 Characteristics of favorable reservoirs

To effectively evaluate reservoirs and predict the distribution of favorable areas, it is necessary to have an accurate understanding of the characteristics of favorable reservoirs. Porosity is the core evaluation index to measure reservoir quality. Therefore, in this study, porosity was compared with field production data to find out the relationship between them. After that, the reservoir lithofacies was analyzed systematically based on high-yield coring wells, to find out the favorable reservoir lithofacies characteristics from both macro and micro perspectives.

4.1.1 Porosity characteristics of favorable reservoirs

In traditional reservoir evaluation, physical property is the direct index to measure the quality of reservoir. Usually, the higher the porosity of the reservoir drilled, the greater the fluid productivity of a single well will be. In this study, the volume of produced natural gas, crude oil and formation water were converted into in-situ volume. In the process of natural gas conversion, dissolved gas and volume coefficient were considered, where the crude oil was converted into formation density, and formation water was converted into average value of field statistical density. After that, the porosity values of the 17 wells and the percentage of samples with porosity of over 1% were counted respectively. Finally, the three points were projected in the same coordinate system (Fig. 3). The results show that there is no obvious correlation between single well fluid output and reservoir porosity, which indicates that the traditional reservoir evaluation method based on porosity is not applicable to the evaluation of tight reservoirs in the study area.

4.1.2 Reservoir lithofacies types

Since the reservoir porosity is unable to evaluate the tight reservoir in the study area, the macro-lithofacies and micro-structural characteristics of reservoir rock from high-yield coring wells were analyzed to study the lithofacies characteristics of favorable reservoirs.

The coquina petrofabrics of Da’an’zhai Member mainly include shell grains, clay-muddy matrix, micrite, sparry calcite cement, recrystallized coarse and gigantic calcite, etc. These petrofabrics have different contents and occurrences in different primary sedimentary environments and later diagenetic environments, resulting in diverse coquina. According to the differences of mineral composition and content of the coquina fillings and the degree of recrystallization, the coquina in Da’an’zhai Member can be subdivided into crystalline coquina, sparry coquina, micrite-bearing coquina, clay-bearing coquina, micrite coquina, clayey coquina, organic rich clayey coquina, kast breccia limestone and calcite dolomite (Pang et al., 2018). In this study, the microstructures of 29 reservoir samples were observed, and the oil-bearing observation technology was used to find out the rock types and structural characteristics of favorable reservoirs. By observing hand specimens macroscopically and slices microscopically, 10 types of lithofacies were identified in the well (Fig. 2 and Table 1). Among them, the coquina includes crystalline coquina, sparry coquina, micrite-bearing coquina, clayey coquina, micrite coquina and clayey coquina, which basically cover all common types of coquina.

In terms of microstructure and composition, 6 types of coquina differ distinctively. The sparry coquina is cemented with sparry calcite between shells, occasionally with micrite or clay mineral, with a content of mud-grade fillings of less than 5% (Fig. 4a–b). The crystalline coquina is formed by intensive recrystallization of primary

<table>
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<th>Lithologic code</th>
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shell particles or cements, in which the calcite crystals vary from coarse to medium-fine and have rich cleavages (Fig. 4c–d). The shell of micritic-bearing coquina is filled by a small amount of micritic calcite particles with a content of 5%–25%, occasionally with shell fragments (Fig. 4e–f). The interstitial materials of micritic coquina are mainly micritic calcite crystal particles too, but higher in content, ranging from 25%–50% (Fig. 4g–h). Clay-bearing coquina has mainly clay filling between shells, with an interstitial material content of 5%–25% (Fig. 4i–j); The clayey coquina is filled by clay impurities between shells, with a clay content of 25%–50% (Fig. 4k–l).
4.1.3 Favorable reservoir lithofacies

After the lithofacies types of reservoirs in high-productivity wells were sorted out, the types and development degree of reservoir space of the six types of coquina in the study area were analyzed by casting thin sections and field emission scanning electron microscopy (FESEM). Subsequently, the oil-bearing degrees in different reservoir spaces of different rocks were confirmed by fluorescent thin sections and environmental scanning electron microscopy (ESEM) (Fig. 5). Finally,
the favorable degrees of various lithofacies were determined by the development degree of reservoir space and their oiliness (Table 2). Comprehensive study shows that the sparry coquina has the most reservoir space, including broken micro-fractures, shell edge fractures, calcite intergranular dissolved pores, shell interparticle dissolved pores and shell intragranular dissolved pores, among them, the first three types are higher in both development degree and oiliness. In addition to the sparry coquina, crystalline coquina is characterized by two types of micro-fractures that can act as dominant migration channels and is the second most favorable reservoir rock. Micrite-bearing coquina is inferior to the former two in types and oiliness of reservoir space. The remaining three types of coquina are much poorer in development degree and oiliness of reservoir space. The remaining three types of coquina are much poorer in development degree and oiliness of reservoir space than the former three types. According to the development degree and microscopic oiliness of reservoir space, the six types of coquina are ranked as follows: sparry coquina > crystalline coquina > micrite-bearing coquina > micrite coquina > clay-bearing coquina > clayey coquina.

4.2 “Five-step” evaluation method of favorable reservoirs

After identifying the lithofacies and micro-characteristics of favorable reservoirs, a “five-step method” to evaluate favorable reservoirs suitable for the study area was established from the perspective of the formation mechanism of favorable reservoirs.

4.2.1 First step: Favorable lithofacies evaluation

Sparry coquina and crystalline coquina are the most favorable reservoir rocks. By comparing the lithology and logging curve characteristics systematically, it was found that there is a good correspondence between GR value and the lithology of coquina (Table 3). The GR of the two kinds of most favorable reservoir rocks, sparry coquina and crystalline coquina, are less than 30 API, while the GR of the other four types of coquina are more than 30 API. Therefore, GR less than 30 API is an effective index to identify favorable reservoir rock in the study area, and can be used for subsequent evaluation of favorable reservoirs.

4.2.2 Second step: Reservoir thickness evaluation

After making sure that the sparry coquina and crystalline coquina are the most favorable reservoir rocks, according to the evaluation of conventional reservoirs, the thicker the high-quality reservoir, the more favorable the reservoir will be. Meanwhile, the reservoir thickness is also closely related to the formation of fractures (McGinnis et al., 2015). Thus, the relationship between the thickness of favorable reservoir rocks and the
Table 3 Corresponding GR of different kinds of coquina

<table>
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production effect was analyzed from the perspective of the whole study area and the specific oilfield. Firstly, 41 wells in G oilfield were selected, and the cumulative thickness of coquina with GR < 30 API in them was counted. The intersection plot of the thickness and the annual average oil and gas production (oil and gas equivalent/ton) of them was plotted (Fig. 6). The results show that there is a significant normal distribution relationship between the thickness of coquina with GR < 30 API and the annual average oil and gas production, that is, there is an optimum thickness range of reservoir. After finding this rule, the thickness map of coquina with GR < 30 API in Da’anzhai Member of central Sichuan area was superimposed with the oil and gas production of wells. The overlapping results are similar to the thickness-production statistics of Gongshanniao oilfield: The industrial oil and gas wells largely have reservoirs of 3 - 18 meters thick, and the oil and gas wells with reservoir thickness greater than 18 meters or less than 3 meters are much fewer (Fig. 7). Thus, the optimum thickness of the favorable reservoir rocks in
Da’anzhai Member is 3–18 meters.

### 4.2.3 Third step: Multi-scale fracture evaluation

Since the matrix porosity in the carbonate reservoir is always low and poorly connected, joints and faults are essential to connect vugs and provide permeability (Antonellini and Molloma, 2000). Microfractures can improve storage and permeability of the reservoir (Zeng, 2010). During development of tight oil, the fractures often act as the dominant channels to give high yield (Zou et al., 2012; Ferrill et al., 2014; Lyu et al., 2016; Gottardi and Mason, 2018). Previous explorations of the Jurassic reservoirs in central Sichuan also found that fractures had a great impact on oil well productivity, and high productivity was often obtained in fracture-developed areas (Zhai, 1989). Limestone has high content of carbonate minerals and thus high brittleness, so it is easier to form fractures (Feng et al., 2015). Production performance also shows that Jurassic tight oil reservoirs in central Sichuan have typical dual media seepage characteristics, and fracture is the dominant factor leading to early high production (Li et al., 2017). Therefore, fracture is an important evaluation index for tight oil reservoirs, and it is a favorable factor in the enrichment stage and development stage of tight oil. The natural fractures provide the main path for fluid flow in tight oil reservoirs and can control the flow direction in the subsurface (Gong et al., 2019).

This study shows that the number of fractures in the...
coquina of Da’anzhai Member is inversely proportional to the size, and the smaller the size, the larger the number. During core observation, the number of fractures able to be seen by naked eye in 10 wells was counted, the results show the fractures have an average linear density of 0.3/m. Microscale statistics show that the average surface density of micro-fractures is in the range of 1–10 pics/mm² at the optical microscopic scale. Under the electronic microscopic scale, the number of micro-fractures of three samples were counted with the vision area of 0.0043 mm², 0.0029 mm² and 0.010101 mm², and the average surface densities were 1396.14 pics/mm², 1039.17 pics/mm² and 1088.62 pics/mm², respectively. Comparing with the fracture surface density under optical microscopy, the difference between the two densities is 100–1000 times. Under this law of fracture development, large faults form the trunk, while small and medium fractures make up the framework, and micro-fractures form network (Fig. 8). Thought most fracture networks exist at a smaller resolution than current seismic data can resolve (Burberry and Matthew, 2017), previous study shows that carbonate fractures are more developed in the areas of faults and folds, and these places are favorable areas for the formation of multi-scale fractures (Pan et al., 2013). In addition, North America’s experiences of tight oil exploration also shows that in areas with large formation deformation such as nose structures, the fractures are more developed and tight oil is more likely to enrich. Elm Coulee Oilfield of Baken Formation is a typical example (Sonnenberg and Pramudito, 2009). Based on the structural map of the bottom of the Da’anzhai Member, the faults, folds and structural noses were defined as fault development areas.

4.2.4 Fourth step: Evaluation of organic acids in source rocks

Generally speaking, in the middle diagenetic A1 stage (with $R_o$ of 0.5–0.7%), the organic matter in source rocks had decarboxylation before large-scale hydrocarbon generation, and generated a large amount of organic acid. The organic acid migrated into the reservoir before enrichment of tight oil, dissolving unstable particles and cements in the reservoir into pores which would act as effective reservoir space (Tao et al., 2015). In central Sichuan, thick source rocks are developed in the middle of Da’anzhai Member (Da 1, Sub-member) and reservoirs are in the upper and lower parts of source rocks, making it easy for the large amount of organic acid water discharged from source rocks to entry the reservoirs. In addition, the multi-scale fractures formed before the peak of organic acid generation, as the dominant migration channels, further promoted the dissolution of acidic formation water to reservoirs. Systematic microscopic observation also shows (Fig. 5) that there are a large number of small secondary dissolved pores in the coquina of Da’anzhai Member, which are a major type of reservoir space in the study area, and together with multi-scale fractures, constituting the dual pore-fracture media (Pang et al., 2018). Therefore, the area with large amount of acidic formation water would have a higher probability of favorable reservoir development, and acidic formation water is undoubtedly an important indicator of favorable reservoir evaluation. In this study, the quantitative evaluation of this index was transformed into the evaluation of source rocks. The better the quality of source rocks, the larger the scale of hydrocarbon generation and the more the discharged organic acid would be. By mapping the geochemical indices of source rocks on the plane and comparing them with the distribution of tight oil wells in the study area, the source rock indices of the organic acid enrichment area in the study area were defined (Table 4).

### 4.2.5 Fifth step: Multi-factor overlapping evaluation

The formation of tight oil and gas sweet spots often requires the combination of multiple factors. Therefore, on the basis of the evaluation of these factors separately, the reservoir “sweet spots” need to predicted by combining all the above factors. In this step, the individual factors were mapped, and then the favorable area of each factor was defined according to the graded evaluation criterion of each factor. Finally, the favorable reservoir distribution area was defined by overlapping all the maps of the factors, which is the area where all factors are favorable.

Firstly, according to the lithofacies characteristics and logging evaluation criterion of favorable reservoirs, the isopach map of coquina with GR < 30 API in the study area was used as the bottom map of favorable reservoir evaluation (Fig. 9a). Then, according to thickness evaluation, the area with the reservoir thickness of 3–18 m was taken as the range for favorable reservoir development. Based on the evaluation index of favorable area of organic acid in source rocks, class I and II areas on the plane were identified (Fig. 9b). Next, the zones with high structural development such as faults, folds and structural noses were marked as favorable zones for multi-scale fractures (Fig. 9c). Finally, the remaining three factors were projected on the isopach map of favorable lithofacies for overlapping to seek out the areas where all factors were favorable to be the favorable reservoir development areas (Fig. 9d). At last, 7 class I and 9 class II favorable reservoir areas were identified in the central Sichuan.

### 5 Conclusions

This work utilized integrated approaches to analyze the reservoir characteristics and evaluation methods of profitable tight oil reservoir of lacustrine coquina. The conclusions can be summarized as follows:

1. The analysis of production and porosity showed that porosity can’t evaluate the favorable reservoirs in the study area accurately.

<table>
<thead>
<tr>
<th>Class</th>
<th>Parameter</th>
<th>Index</th>
<th>Class</th>
<th>Parameter</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I area</td>
<td>Mudstone thickness</td>
<td>&gt;20 m</td>
<td>Class II area</td>
<td>Mudstone thickness</td>
<td>10–20 m</td>
</tr>
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<td>&gt;1.4%</td>
<td></td>
<td>TOC</td>
<td>&gt;1.4%</td>
</tr>
<tr>
<td></td>
<td>Hydrocarbon-generating intensity</td>
<td>&gt;30×10⁴ t/km²</td>
<td></td>
<td>Hydrocarbon-generating intensity</td>
<td>20–30×10⁴ t/km²</td>
</tr>
</tbody>
</table>
Fig. 8. Multiscale fracture structure model of coquina in Da’anzhai Member.

Fig. 9. Comprehensive evaluation map of favorable reservoirs of Jurassic Da’anzhai Member in central Sichuan Basin. 
(a) Isopach map of favorable coquina of Da’anzhai Member with GR < 30 API; (b) evaluation map of high-quality source rocks in Da’anzhai Member; (c) evaluation map of multi-scale fracture development area in Da’anzhai Member; (d) evaluation map of favorable reservoir distribution based on overlapping maps of several factors.
(2) Reservoir microscopic study revealed that the sparry coquina was the most favorable reservoir lithofacies among the six main lithofacies of the coquina in Da’anzhai Member. Based on systematical micro-analysis and litholectric calibration, GR<30API was deemed an effective evaluation index of favorable reservoir lithofacies, then the planar favorable lithofacies map was compiled, and the favorable lithofacies thickness was combined with the production data, which showed the optimum thickness of favorable lithofacies was 3–18 m.

(3) Multiscale fracture network is developed in the study area, the number of fractures is inversely proportional to the size, the smaller the scale of fracture, the larger the number of the fracture will be. Large faults form the trunk, small and medium fractures make up the framework and micro-fractures form the network. Multiscale fracture network is an important favorable factor for tight reservoir. Based on the research and production experience at home and abroad, it is believed that the areas with severe deformation, such as faults, folds and tectonic noses, are favorable areas for multi-scale fractures.

(4) The organic acid discharged from hydrocarbon generation in source rocks provided material conditions for the formation of secondary dissolved pores. Horizontal distribution of acidic formation was evaluated by using source rock index.

(5) On the basis of single factor analysis, the individual factors were combined to figure out the favorable reservoir of coquina. A set of “five-step” evaluation process has been established, and favorable reservoir areas have been sorted out.

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