Classification of flow standards of carbonate formation in Bereketli-Pirgui gas field

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Abstract. Callovian-Oxfordian carbonate formation in Bereketli-Pirgui gas field as an example was selected. This paper describes three methods for quantitative division of flow standards based on parameters such as pore throat size, FZI’s (Flow Zone Index), storage capacity, and flow capacity. In this connection, the results can not only reflect the meter-scale heterogeneity of reservoirs around wellbore, but also meet the requirements of the minimum number of flow standards in reservoir numerical simulations.

Based on the measured data of core porosity and core permeability of Callovian-Oxfordian formation, rock types are firstly identified, then the main flow standards are determined according to the FZI, and finally the main hydraulic flow standards are divided in the stratigraphic framework according to the storage capacity and flow capacity. In comparison with the single factor flow standard classification method, this method can not only realize the classification of flow standards of different scales, but also help to compare different flow standards with each other in the sequence of stratigraphic framework.

The result indicates that Callovian-Oxfordian formation has 5 main rock types (i.e. micritic limestones, bioclastic microcrystalline limestones, sparry bioclastic limestones and algal limestones), 8 different flow standards (i.e. FU1-FU8) and 4 hydraulic flow standards (i.e., flow channel, storage-flow unit, storage unit and barrier unit). The classification results with different methods have a good agreement.

1. Introduction

Carbonate reservoirs display strong heterogeneity from microscopic pore scale to macroscopic reservoir scale [1]. How to correctly identify and divide flow units is very important to both fine geological modeling and numerical simulation [2].

A flow standard refers to a continuous stratigraphic interval with similar rock types and similar reservoir properties change rates [3]. Different researchers have different schemes for the classification of carbonate flow standards according to different requirements. In this paper, three methods were used to divide flow standards of Callovian-Oxfordian carbonate reservoir in Bereketli-Pirgui gas field. Firstly, the main rock types are determined by pore throat size using the Pittman porosity-permeability plot. Secondly, the main flow standards and the porosity-permeability relationship of different flow standards are determined using the FZI (flow zone indicator) method. Finally, hydraulic flow standards are divided using the Stratigraphic Modified Lorentz Plot (SMLP), the Modified Lorentz Plot (MLP) and the Stratigraphic Flow Profile (SFP).
By comprehensively using the three methods, (i) the main flow standards and their rock types in the formation can be determined, and (ii) micro-heterogeneity and meter-scale macro-heterogeneity can be reflected. In addition, the main pay zones of reservoir can be determined according to storage capacity and flow capacity providing a quantitative geological basis for optimization of perforation and potential area.

2. Methodology

2.1. Data used
The data used include the description of 450m cores from 9 wells, data of petrophysical property measurements data of 1025 cores and logging data.

2.2. Main methods

2.2.1. Classification of rock types based on microscopic pore throat size. Rock types refer to a group of rock units that undergo similar sedimentary processes and similar diagenetic transformations. There is a significant correlation between porosity and permeability of the same rock unit and it has similar flow characteristics due to the same petrophysical properties [4].

According to Winland experimental results [5] [6], when the mercury injection saturation is 35%, the pore networks in rock samples are mutually connected to form continuous and effective flow channels. In this case, the pore throat radius (R35) can reflect the size of effective pore throats. However, the Winland equation is mainly applicable to sandstones dominated by primary pores. In order to reflect the complex of carbonate reservoir, Pittman equation [7] suitable for carbonate reservoirs is used to determine R35. The calculation method is below:

\[
\log R_{35} = 0.255 + 0.565 \log k - 0.523 \log \phi_e
\]  

(1)

Where, \(k\) is air permeability (mD), \(\phi_e\) is core porosity (%), and \(R_{35}\) is the pore throat radius (um) when the mercury injected saturation is 35% in capillary pressure tests.

Figure 1 is the porosity-permeability cross plot obtained using the Pittman method. The curves in the figure are equal pore-throat curves at different levels of throat radius, and the sample points distributed along the equal-pore throat curves are rock units with similar flow characteristics. As shown in Figure 1, there are five types of pore throats in Callovian-Oxfordian formation, namely Nanoport (\(R_{35}<0.1\)um), Microport (\(0.1<R_{35}<0.5\)um), Messoport (\(0.5<R_{35}<2\)um), Macroport (\(2<R_{35}<10\) um) and Megaport (\(10<R_{35}<100\)um).

![Figure 1](image)

Figure 1. Pittman porosity-permeability plot.

Table 1 is the statistics of rock samples with different pore throat sizes. According to the table 1, the proportion of rocks with Megaport is 1.4%, and the main rock types are micritic limestones with developed fractures and biohermal limestones; the proportion of rocks with Macroport is 8.4%, and
the main rock types are bioclastic limestones and algal limestones; the proportion of rocks with Messoport is 15.3%, and the main rock types are microcrystalline-sparry bioclastic limestones; the proportion of rocks with Microport is 43.2%, and the main rock types are bioclastic microcrystalline limestones; the proportion of rocks with Nanoport is 31.6%, and the main rock types are micritic limestones. Obviously, the main rock types in the formation are bioclastic microcrystalline limestones and micritic limestones, the main pore throat types are Nanoport and Microport.

Table 1. Frequency of rock types defined by Pittman Method.

| Rock type | Nanoport | Microport | Messoport | Macroport | Megaport |
|-----------|----------|-----------|-----------|-----------|----------|
| Frequency | 281      | 384       | 136       | 75        | 12       |
| Percentage (%) | 31.6 | 43.2 | 15.3 | 8.4 | 1.4 |

2.2.2. Classification of flow standards based on FZI. The division of flow standards based on petrophysical characteristics is realized mainly using the statistical method based on the modified Kozeny-Carman equation and the average hydrodynamic radius [8]. The method is used to determine different flow standards based on FZI [9][10], the core porosity and core permeability, as well as rock quality index (RQI) and pore-matrix ratio (PMR) [11][12].

RQI is calculated according to the following equation:

\[
RQI = 0.0314 \times \sqrt{\frac{k}{\Phi}}
\]  

(2)

Where, \(k\) is air permeability (mD), \(\Phi\) is rock porosity (v/v).

PMR is calculated according to the following equation:

\[
PMR = \frac{\Phi}{1-\Phi}
\]  

(3)

FZI is calculated according to the ratio of RQI to PMR:

\[
FZI = \frac{RQI}{PMR}
\]  

(4)

Take the logarithm to the two sides of the equation to obtain the following equation:

\[
\log(RQI) = \log(FZI) + \log(PMR)
\]  

(5)

Ideally, the sample points with the same FZI value are located on the same straight line in the RQI versus PMR log-log coordinate system, and the sample points with different FZI values are located on other straight lines parallel to each other. The sample points on the same straight line have similar pore throat distribution, so they form the same flow standards (Figure 2). Accordingly, each straight line reflects that the same flow standard has a similar FZI value.

Figure 2. Log-log plot of RQI versus PMR.

According to the RQI vs. PMR plot, the Callovian-Oxfordian carbonate formation can be divided into 8 flow standards, and the quantitative classification criterion is as follows:
FU1: \( \log FZI \geq 1.73 \)
FU2: \( 1.29 \leq \log FZI < 1.73 \)
FU3: \( 0.79 \leq \log FZI < 1.29 \)
FU4: \( 0.34 \leq \log FZI < 0.79 \)
FU5: \( -0.09 \leq \log FZI < 0.34 \)
FU6: \( -0.45 \leq \log FZI < -0.09 \)
FU7: \( -0.86 \leq \log FZI < -0.45 \)

FU8: \( \log FZI < -0.86 \)

According to the distribution frequency histogram of different flow standards (Figure 3), the main flow standards in the formations are FU5, FU6 and FU7, followed by FU3 and FU4, and other flow standards are relatively undeveloped.

![Flow Units Frequency Percentage histogram](image)

**Figure 3.** Frequency percentage histogram of FUs.

2.2.3. **Classification of hydraulic flow standards based on the storage capacity and flow capacity.**

A hydraulic flow standard is a combination of rock units with similar storage and flow characteristics. The basis for the classification of hydraulic flow standards is the storage capacity and flow capacity of formation. The Stratigraphic Modified Lorentz Plot (SMLP) reflects the specific location of a flow standard in the stratigraphic framework according to storage capacity and flow capacity, and is the best graphical method for evaluating the minimum number of hydraulic flow standards in reservoir.

Firstly, it is important to calculate the storage capacity\( (\theta h) \), flow capacity \( (kh) \), and cumulative percentage of sample interval points by depth in the stratigraphic framework using core measurement data, to build the Stratigraphic Modified Lorentz Plot (SMLP) (Figure 4) in the stratigraphic framework, and to determine different hydraulic flow standards on the SMLP according to the inflection points of the curve. Figure 4 shows that the well P1 can be divided into 8 hydraulic flow standards. As shown in the figure, the larger slope of the line segment, the stronger flow capacity of the depth segment (④ and ⑦ in Figure 4); the flatter of the line segment, the worse flow capacity of the segment (③ and ⑧ in Figure 4).

Then, it can be arranged in a descending order according to percent flow capacity divided by percent storage capacity, and constructed the final modified Lorenz plot (MLP, Figure 5) and the stratigraphic flow profile SFP (Figure 6) on the basis of correction of parameters such as R35, K/\( \phi \), etc.

The SFP mainly includes stratigraphic correlation curve (GR), core porosity (Pore_core), core permeability (K_core), rock quality index (RQI), pore throat radius (R35), storage capacity percentage (\( \theta h\% \)) and flow capacity percentage (\( kh\% \)) curve.
It can be seen from the MLP (Figure 5) that well P1 can be divided into four main hydraulic flow standards:

1. Flow channels: composed of ②, ④ and ⑦, the flow capacity is obviously higher than the storage capacity; the storage capacity is only 8%, and the flow capacity accounts for 87% in the entire interval; the lithology is mainly composed of micritic limestones with fractures, the average pore throat radius R35 is 17μm and the main flow units are FU1 and FU2.

2. Storage-flow standard: composed of ⑤, the storage capacity is higher than the flow capacity; the storage capacity is 16%, and the flow capacity accounts for 8% in the entire interval; the lithology is mainly bioclastic limestones, the average pore throat radius R35 is 2.7μm and the main flow units are FU3, FU4 and FU5.

3. Storage standards: composed of ①, ③ and ⑥, the storage capacity is obviously higher than the flow capacity; the storage capacity is 70% and the flow capacity accounts for 4% in the entire interval; the lithology is mainly micritic-microcrystalline limestones; the average pore throat radius R35 is 0.13μm and the main flow units are FU6 and FU7; the production of the well can be greatly increased through acidification.

4. Barrier standard: composed of ⑧, the storage capacity is slightly higher than the flow capacity, the flow capacity accounts for 1% in the entire interval, and the storage capacity accounts for 6%. The flow standard consists of micritic limestones with underdeveloped pores and fractures, the average pore throat radius R35 is only 0.02μm, and the main flow unit is FU8, which is the main barrier and interlayer.

3. Conclusion and discussion

This paper presents three methods for classification the flow standards of carbonate formation from different perspectives based on core porosity and core permeability. The methods are very good practicable on the premise that core data are complete and strongly representative, and the fracture type is mainly micro-fracture. Compared with conventional net pay evaluation methods, the method integrate parameters such as rock type, flow standard, storage capacity, and flow capacity can greatly improve the evaluation of the storage and flow potential of formation, and are forward-looking method. The first two methods mainly reflect the heterogeneity of reservoirs from a static perspective, and the third method mainly is suitable for storage and flow capacity of reservoir from a dynamic perspective.

The three methods display reservoir characteristics from different perspectives, but they have good agreement (Figure 6). On the whole, the flow channels in hydraulic flow standards correspond to the FZI-based identified standards with high reservoir quality (brown and orange in the FUs track); storage standards and storage-flow standards usually correspond to the FZI-based identified flow standards with medium reservoir quality (light blue and green in the FUs track), and barrier standards usually correspond to the FZI-based identified units with low reservoir quality (dark blue in the FUs track).

For example, the three high-permeability sections (the red sections of the last track in Figure 6) of well P2 have the largest pore throat radius (R35) and rock quality index (RQI); the main storage-flow...
standard (3166-3172m) corresponds to FU3 (track 9 green in Figure 6), and the lithology of FU3 is micritic limestones with developed small pore throats (average R35 is 0.25µm); the main storage standard (3176-3189m) corresponds to FU2 (track 9 light blue in Figure 6), and the lithology of FU2 is mainly micritic limestones with developed micro-pore throats (average R35 is 0.09µm).

It should be noted that the adoption of only the method for classification of carbonate rock types based on pore throat size may lead to large errors because of the impact of strong transformations (such as fracturing, dissolution, cementation, etc.) of carbonate rocks after diagenesis and the same type of rocks’ possible large difference in physical properties.

The FZI-based division method for flow standard is based on the relationship between porosity and permeability. The result of the method can improve the accuracy of logging interpretation of reservoir parameters and especially the accuracy of permeability (Figure 7 shows that the porosity and permeability of different flow standard have very good nonlinear relationship), and can also better reflect the vertical heterogeneity (Figure 6) of reservoirs and help improve geological model precision.

The classification of hydraulic flow standards helps identify main pay zones, the result is more suitable for reservoir numerical simulation.
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