Study on 3D Permeability Modelling of Carbonate Reservoir Based on Flow Unit Classification

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Abstract: RQI (Rock Quality Index) and FZI (Flow Zone Index) have proved to be effective methods of dividing the flow unit in the carbonate reservoir of the R oil field. The method utilizes the porosity and permeability of the core rock samples to divide the flow unit. The field consists of six flow units, and they represent different flow characteristics. The FZI can be accurately predicted by establishing a mathematical model of the log curves where core is not available, and the FZI/DRT (Discrete Rock Type) model of the whole reservoir is established by geostatistics method. With the DRT model and the porosity model, the permeability model can be estimated by using the characteristics of each flow unit with unique porosity-permeability relationship. The results show that the permeability model established by this method does not require a perm multiplier, the difficulty of curve fitting is greatly reduced and the work efficiency is improved in the numerical simulations.

1 INTRODUCTION

As an important parameter of oilfield development, rock permeability is generally converted into a continuous permeability curves through the petrophysical parameter model. Permeability is not only related to porosity but also to pore shape and pore size distribution. The porosity and permeability of single-porosity sandstone reservoirs generally show a simple function change. The established 3D model of permeability can be converted from 3D model of porosity. In carbonate reservoirs, however, this simple functional relationship is hardly valid due to the properties of carbonate rocks and the properties that are easily changed. The pore-perm relationship from the core test is very complicated, often with small change in porosity, and the permeability changes by several orders of magnitude or even the same porosity value corresponds to different magnitudes of permeability. This phenomenon does exist in the actual production of carbonate reservoirs in R oil field in Indonesia, and the permeability cannot be matched with the actual output. Therefore, R oilfield needs some method to establish a permeability model that can truly reflect the geological conditions of the oilfield and reduce the uncertainty in development. Based on this, the authors put forward the application of porosity and permeability of rock samples, using flow unit index method to divide flow units, establishing corresponding permeability model in each flow unit, and achieving the purpose of improving permeability model evaluation accuracy.

2 THE BASIC THEORY OF FLOW UNITS

The concept of flow units was first proposed by Hearn (1984). He defined a reservoir zone with vertical and horizontal continuum with similar permeability, porosity and bedding features as flow units (Hearn et al., 1984). After the study by different experts and scholars, the flow unit has more and deeper understanding. W. J. Banks et al. Consider flow units to be further subdivided according to changes in the physical and petrophysical properties that affect the fluid flow in the rock (Ebanks, 1987). D.C. Barr et al. (1992) consider flow units as a rock block with similar water features in a given rock(Barr and Altunbay, 1992). Yinan Qiu et al. consider that the flow unit is a naturally occurring

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fluid flow channel due to the heterogeneity of the reservoir, the baffle and the by-pass conditions (Qiu and Wang, 1996). Longxin Mu believes that the flow unit is a reservoir unit that is consistent with percolation characteristic due to boundary constraints, discontinuous thin barrier layers, various sedimentary micro-interfaces, small faults, and permeability differences within an oil sands body (Mu et al., 1996).

The authors through a large number of literature research believe that D.C.Barr's definition on the definition of flow unit is Archie's early extension of the definition of rock type (Archie, 1952). Archie believed that similar rock types were deposited under similar geological conditions and underwent similar diagenetic processes to form a type of rock with unique pore structure and wettability. The theoretical basis of the method adopted in this paper is D.C. Barr's definition of flow units.

The flow units have the following features (Amaefule and Altunbay, 1993; Gunte et al., 1997; Guo et al., 2005) 1)Each flow cell has similar depositional conditions and diagenetic reformation environment; 2)Under the proper classification conditions, each flow unit has a unique porosity-permeability curve, a capillary pressure curve (J-function), and a set of relative permeability curves; 3)If properly applied, the flow cell can accurately estimate the permeability of non-coring section and generate a reliable initial water saturation curve; 4)Through the permeability model and oil saturation model build by the facies control of flow units ,the dynamic characteristics and production status of the reservoir can be truly simulated.

There are many ways to identify flow units (Varavur et al., 2005; Tan and Lian, 2013; Liu et al., 2011), pore throat structure parameter method, flow zone index method (FZI/DRT), pore throat radius method, comprehensive parameter method, outcrop depositional interface analysis method, production dynamic parameter method and cluster analysis method. At present, the mainstream technology of quantitative flow unit classification of carbonate reservoirs is the flow zone index (FZI) method and Winland'S R35 method. (Wang et al., 2017; Chekani and Kharrat 2009; Tillero, 2012; Shabaninejad and Haghighi, 2011; Betancourt, 1997)

3 FZI METHOD

FZI method include two petrophysical methods, Rock Quality Index (RQI) and flow unit analysis. The Rock Quality Index reflects the reservoir's ability to store and seep. Flow unit indicators can be inferred by the rock quality index, which reflects the seepage abilities of different rock types under current conditions, regardless of the rock deposition in the formation. Porosity and permeability data from core test were used to calculate the flow unit according to the following formula (Amaefule and Altunbay, 1993)

$$RQI = 0.0314\sqrt{\frac{K}{\emptyset_e}} \qquad (1)$$

In formula (1), K is permeability (md), $\emptyset_e$ is effective porosity (%), RQI is rock quality index (μm).

$$\emptyset_z = \left(\frac{\emptyset_e}{1-\emptyset_e}\right) \qquad (2)$$

In formula (2), $\emptyset_z$ is a normalized porosity.

$$FZI = \frac{RQI}{\emptyset_z} = 0.0314\left(\frac{1-\emptyset_e}{\emptyset_e}\right)\sqrt{\frac{K}{\emptyset_e}} \qquad (3)$$

In equation (3), FZI is the flow zone index (μm).

FZI is a continuous variable, which is a parameter that determines the pore structure by combining structural and rock mineralogical and pore throat features, and can accurately describe the heterogeneous characteristics of the reservoir. We can apply statistical rules to convert FZI to discrete variables DRT,

$$DRT = Round[2\,ln(FZI) + 10.6] \qquad (4)$$

In equation (4), DRT is rock type. Equation (4) is merely a simple tool to convert a continuous rock type variable (FZI) into a discrete one (Guo et al., 2005).

392 core samples from 7 wells in R oil field were taken and flow units of the oilfield was calculated according to the FZI method. Table 1 show the results from one such well.

By calculating three parameters RQI, FZI and DRT, the reservoir of R oil field can be classified into 6 flow unit. This helps to build a relationship chart of core porosity and permeability based on the classification of FZI method (Figure 1).

Different colors represent different flow units, and the relationship between core porosity and core permeability becomes regular in each type of flow unit, and each flow unit overlaps with each other to a minimum. Fitting the functional relationship, the porosity and permeability have a power function relationship, the correlation is above 0.8 (Table 2).

Table 1: FZI & DRT calculation results of well_01 in R oil-field.

MD (feet)	Porosity	Permeability (md)	RQI (μm)	FZI (μm)	DRT
3028	0.352	2.9	0.090	0.166	7
3013	0.248	1.4	0.075	0.226	8
3014	0.359	6.4	0.133	0.237	8
3021	0.347	5.7	0.127	0.239	8
3055	0.321	10	0.175	0.371	9
3012	0.304	16	0.228	0.522	9
3027	0.336	27	0.281	0.556	9
3047	0.306	31	0.316	0.717	10
3062	0.381	85	0.469	0.762	10
3052	0.321	57	0.418	0.885	10
3005	0.311	52	0.406	0.900	10
3037	0.346	94	0.518	0.978	11
3059	0.331	88	0.512	1.035	11
3046	0.286	81	0.528	1.319	11

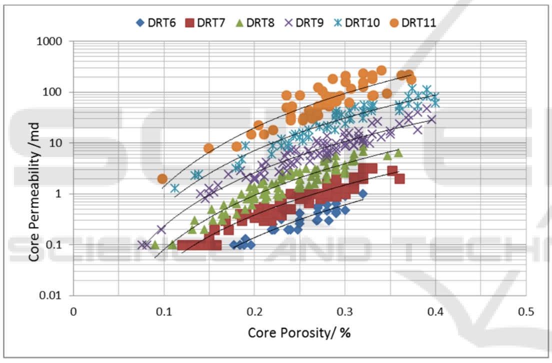
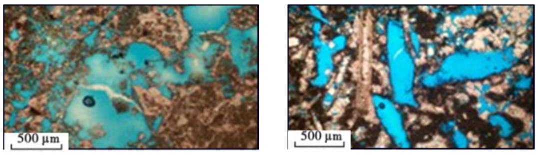


Figure 1: The plot of permeability vs. porosity as classified using FZI.

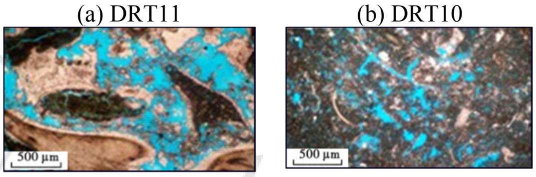
Table 2: The relationship of porosity and permeability in DRT of R oil-field.

Flow Units	Relationship formula	Correlation coefficient
DRT6	$K = 50.353 * \emptyset^{3.6696}$	0.86
DRT7	$K = 84.071 * \emptyset^{3.3506}$	0.921
DRT8	$K = 278.36 * \emptyset^{3.5406}$	0.895
DRT9	$K = 708.36 * \emptyset^{3.4842}$	0.941
DRT10	$K = 2443.9 * \emptyset^{3.6307}$	0.931
DRT11	$K = 9557 * \emptyset^{3.8378}$	0.812

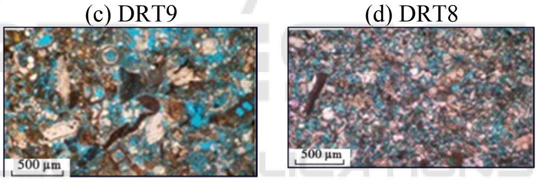
Figure 2 is a photograph of six typical castings thin sections, representing the rock mass of six different flow units in the field. DRT11 development of holes, connected to each other to form a fluid flow connectivity, so the permeability is high. DRT10 development of large holes, connectivity is better. The DRT6 is very dense, the development of clay crystal micropores, porosity and permeability are low, most of the fluid trapped in the microporosity, it is difficult to form a good seepage channel. DRT7-DRT9 followed by the development of micro-mesoporous, mesoporous, mesoporic-macroporous, structural features between the DRT6-10.



(a) DRT11 (b) DRT10



(c) DRT9 (d) DRT8



(e) DRT7 (f) DRT6

Figure2: Typical thin section pictures of the six rock types from the core wells.

The agreement between the two was very good by comparing the experimental core permeability with the permeability calculated by the FZI / DRT method (Figure 3).

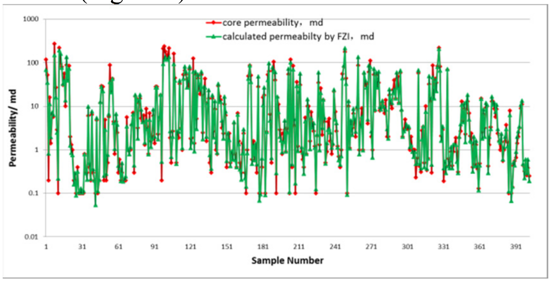


Figure 3: A comparison between core permeability and calculated permeability based on FZI.

Table 3: Coefficient statistics table.

	a	b	c	d	e	f	g
ALL curve	-0.16	0.37	0.17	1.17	0.95	-0.18	-0.88
NO DT curve	-0.5	0.33	-0.05	1.07	0.79	0.22	0
NO SP curve	-0.09	0	0.4	1.1	0.92	0.23	-1.41
NO RD curve	1.33	0.22	-0.33	0	0.38	-0.95	-1.44

4 PERMEABILITY MODEL BASED ON FZI

4.1 Logging Calculation Method of FZI

Flow unit division is based on core data, and its calculation method provides us with a more reliable quantitative template, but the core data is limited after all. How to apply it to a well or even the whole field? Here we use the multiple linear regression method to establish the relationship between log data and FZI.

Several Well log curves that are sensitive to FZI are selected. In this study, six log curves of spontaneous potential(SP), natural gamma ray(GR), resistivity(RD), neutron(NPHI), density(RHOB) and acoustic(DT) were selected and normalized by using the following formula:

$$Nx = (X - Xmin)/(Xmax - Xmin) \tag{5}$$

In equation (5), Nx is the normalized value, X is the logging curve value, Xmin is the minimum value of the logging curve, and Xmax is the maximum value of the logging curve.

Then use multivariate linear regression was used to get the relationship between FZI and each curve, the formula used being:

$$FZI = a + b * SP + c * GR + d * RD + e * NPHI + f * RHOB + g * DT \tag{6}$$

where a=-0.16;b=0.37;c=0.17;d=1.17;e=0.95;f=-0.18;g=-0.89

Since not all wells have these six well logs, the regression equation is also considered with five curves to calculate the FZI value, the results are shown in Table 3

Using formula (6), the FZI curve for all non-coring wells can be calculated.

4.2 Calculation of Permeability Model

The FZI curve is scaled up and the FZI model is built by Sequential Gaussian Simulation conditioned to the porosity model (Figure 4). The FZI model is an interpolation model with continuous variables. In order to characterize different flow units more clearly, the FZI model is transformed into the DRT model (Figure 5) using formula (4). The DRT model is a discrete volume. The data type is similar to sedimentary facies or lithofacies. According to the characteristics of the flow cell, under the proper classification conditions, each flow cell has a unique pore-perm curve. Therefore, under the constraint of the flow cell (under DRT model control), permeability value for each DRT can be calculated to get the permeability model (Figure 6).

The permeability model established in this way can more accurately reflect the geological conditions of the reservoir. In the numerical simulation, it can reduce the inconsistent dynamic characteristics and static characteristics and improve the working efficiency of the numerical simulation. The RQI / FZI method facilitates the study of permeability of carbonate reservoirs.

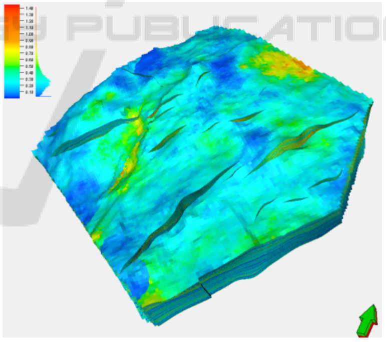


Figure 4: FZI modelling.

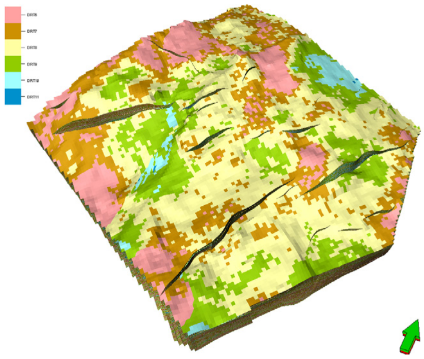


Figure 5: DRT modelling.

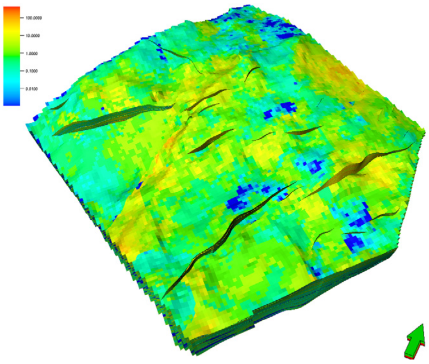


Figure 6: Permeability modelling.

5 CONCLUSIONS

The FZI / DRT method was used to study the flow units of carbonate reservoir in R oil field. According to the experimental results of core porosity and permeability, the reservoir was divided into six different flow units by empirical formula.

As each flow unit has a distinct structure and percolation characteristics, the flow unit can be used as a property to build the 3D model and the permeability model can be built under the flow unit constraints. This method can be used to accurately describe the spatial characteristics of permeability in a carbonate reservoir.

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