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A new method of formation evaluation for fractured and caved carbonate reservoirs: A case study from the Lundong area, Tarim Basin, China

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Abstract: The carbonate reservoirs in the Tarim Basin are characterized by low matrix-porosity, heterogeneity and anisotropy, which make it difficult to predict and evaluate these reservoirs. The reservoir formations in Lundong area experienced a series of diagenesis and tectonic evolution stages. And secondary storage spaces such as fractures and dissolution caves were developed while nearly all the primary pores have disappeared. Based on a summary of different types of storage spaces and their responses in conventional logs, FMI and full waveform sonic logs which are sensitive to different reservoirs, the comprehensive probability index (CPI) method is applied to evaluating the reservoirs and a standard of reservoir classification is established. By comparing the evaluation results with actual well-logging results, the method has proven to be practical for formation evaluation of carbonate reservoirs, especially for the fractured carbonate reservoirs. In reservoir fluid identification, the multivariate stepwise discriminant analysis (MSDA) method is introduced. Combining the CPI method and MSDA method, comprehensive formation evaluation has been performed for fractured and caved carbonate reservoirs in the Tarim Basin. Additionally, on the basis of secondary pore inversion results, another new method of formation evaluation is also proposed in the discussion part of this paper. Through detailed application result analysis, the method shows a promising capability for formation evaluation of complex carbonate reservoirs dominated by various secondary pores such as holes, caves, and cracks.

Key words: Carbonate reservoir, formation evaluation, comprehensive probability index method, discriminant analysis, Tarim Basin

1 Introduction

The carbonate in the Tarim Basin is mainly distributed in the Sinian, Cambrian and Ordovician. The storage space characteristics and distribution of the carbonate reservoirs in the Tarim Basin are mainly controlled by tectonic movement and diagenesis, and not directly related to the sedimentary environment (Xia et al, 2000).

The Palaeozoic carbonate rocks in the Tarim Basin experienced stages of sedimentation, surficial weathering, shallow, intermediate and deep burial. Many different kinds of diagenesis occurred. Due to the effect of compaction, dissolution and cementation, nearly all the primary pores have disappeared. The basement rock has a relatively low porosity and permeability. Meanwhile, these rocks produced a large number of dissolution fractures and caves through weathering, leaching and tectonic evolution of different levels and different periods, which improved the storage capability of carbonate reservoirs. Secondary pores became the dominant storage spaces of carbonate reservoirs in the Tarim Basin (Yang et al, 2004; Xu et al, 2005).

2 Logging responses of different reservoirs

By an integration of core and thin section examination and formation micro-resistivity imaging log (FMI) information, carbonate reservoirs have been proven to be favorable in the Lundong area. Through a comprehensive analysis, the carbonate reservoirs in the Lundong area are classified into four types, fractured reservoir, hole-caved reservoir, caved reservoir and fracture-caved reservoir (Guo et al, 1996; Fu et al, 2006a). In the following section, the logging responses for each kind of reservoir are discussed.

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2.1 Fractured reservoir

Fracture is a very common type of storage space for carbonate reservoirs. If the storage space is dominated by fractures, the reservoir is classified as a fractured reservoir. The matrix porosity and permeability of this type of reservoir is quite low. The logging responses for a fractured reservoir are summarized as follows: 1) Micro-laterolog resistance (RMLL) shows a sharp jump compared with the laterolog deep (LLD); 2) Both laterolog deep and laterolog shallow (LLS) results show low resistivity, but there are significant differences between them. Besides, high angle fractures show a positive separation (LLD>LLS), and low angle fractures shows a negative separation (LLD<LLS); 3) The dipole sonic log shows a V-form interference fringe while FMI displays a sinusoidal curve. All of the logging responses above are shown in Fig. 1.

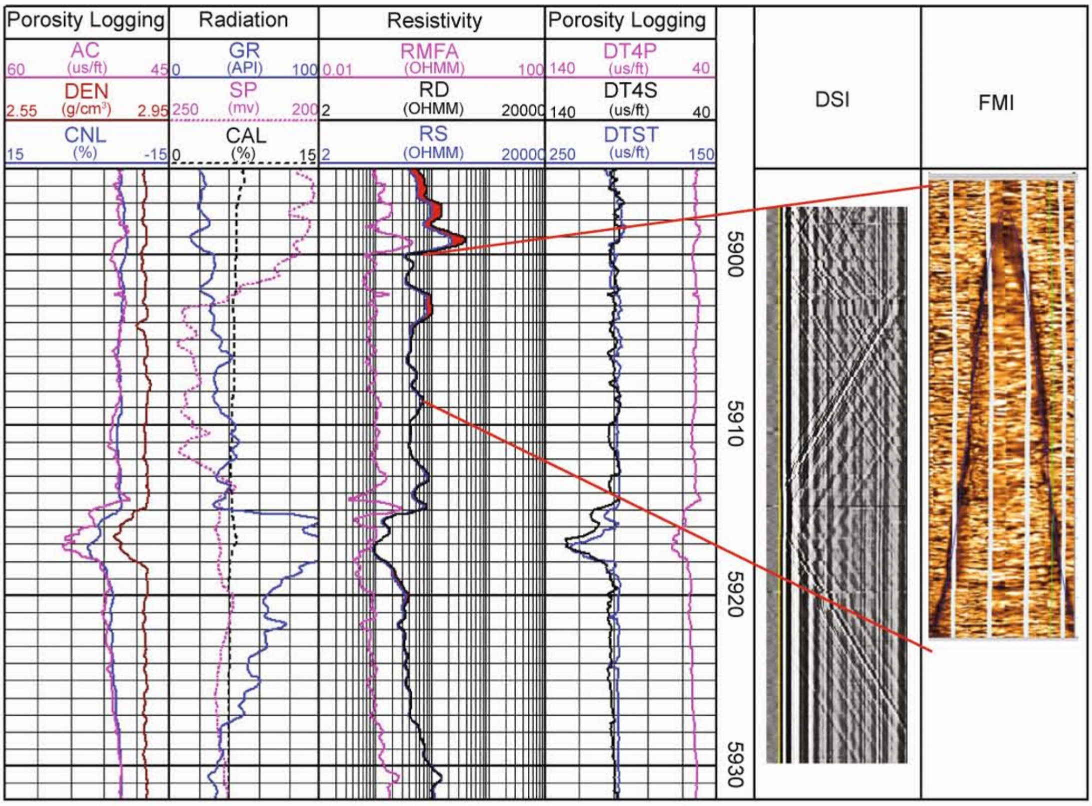

Fig. 1 Logging response of a fractured reservoir (taking Well LG36 as an example)

2.2 Hole-caved reservoir

The storage space and seepage channels of hole-caved reservoirs are made up of both holes and caves with little effect of fractures. The hole-caved reservoirs show irregular black spots in FMI while the dipole sonic log shows a V-form interference fringe. There is no obvious difference between LLD and LLS, but a sharp jump can be recognized in micro-spherical focused log or micro-laterolog (see Fig. 2).

2.3 Caved reservoir

The caved reservoir means that its storage space is made up of caves with little effect of holes or fractures. This type of reservoir shows dark striation in FMI and V-form interference fringes and weak amplitude in the dipole sonic log (shown at the depth of 6,191-6,199 m and 6,218.5-6,250 m in Fig. 3).

2.4 Fracture-caved reservoir

Fracture-caved reservoirs are formed from porous basement rocks cut by fractures. This type of reservoir has the advantages of good permeability influenced by fractures and favorable storage spaces formed by caves. Caves can be developed at the intersection of fractures and the fractures can also be induced. As shown at the depth of 6,199-6,206 m in Fig. 3, the sinusoidal characteristics in FMI for fracture-caved reservoirs are weak compared with those for fractured reservoirs.

3 Reservoir type classification: comprehensive probability index (CPI)

Each kind of logging data carries physical information about the subsurface media, which may reflect the characteristics and development status of reservoir intervals. Formation evaluation of carbonate reservoirs has been discussed by several authors (Wu et al, 1995; Wang and Guo, 2002; Babadagli and Al-Salmi, 2004; Yang et al, 2010; Wang et al, 2010). Jing et al (2005) summarized a systemic method of logging interpretation, which included definition

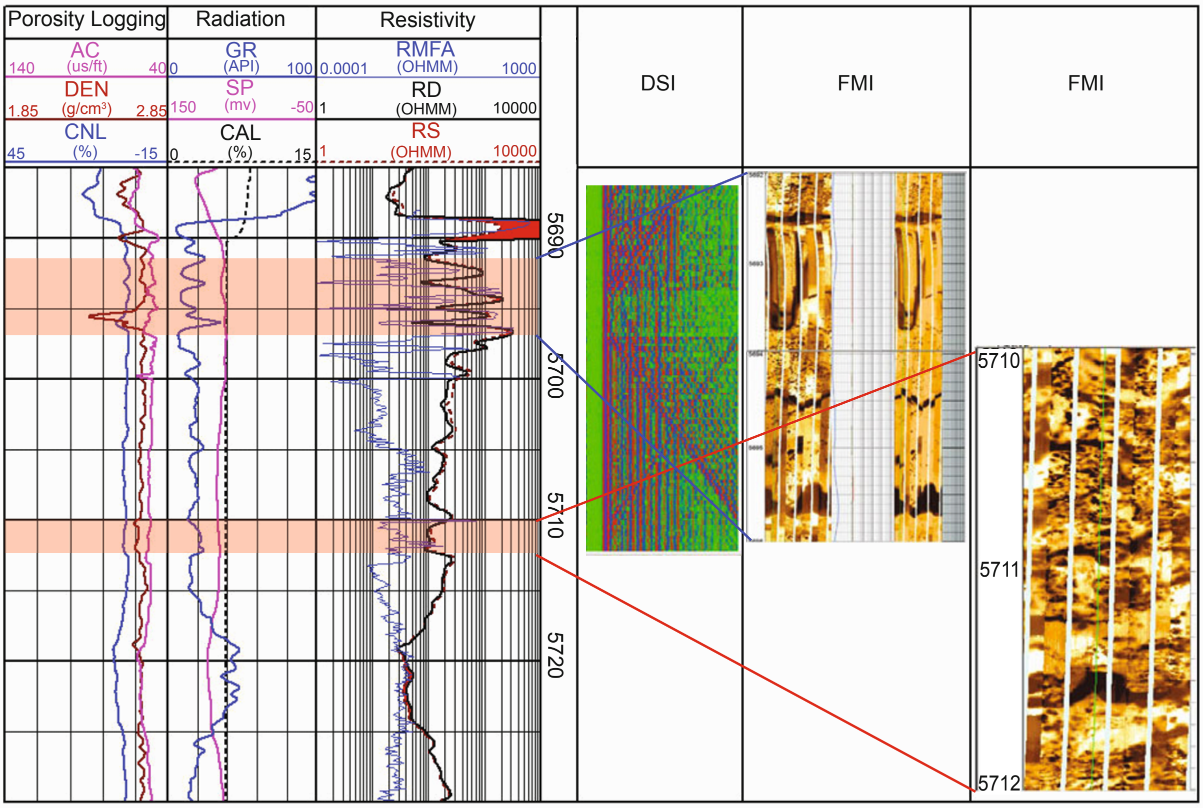

Fig. 2 Logging response of a pore-caved reservoir (taking Well LG39 as an example)

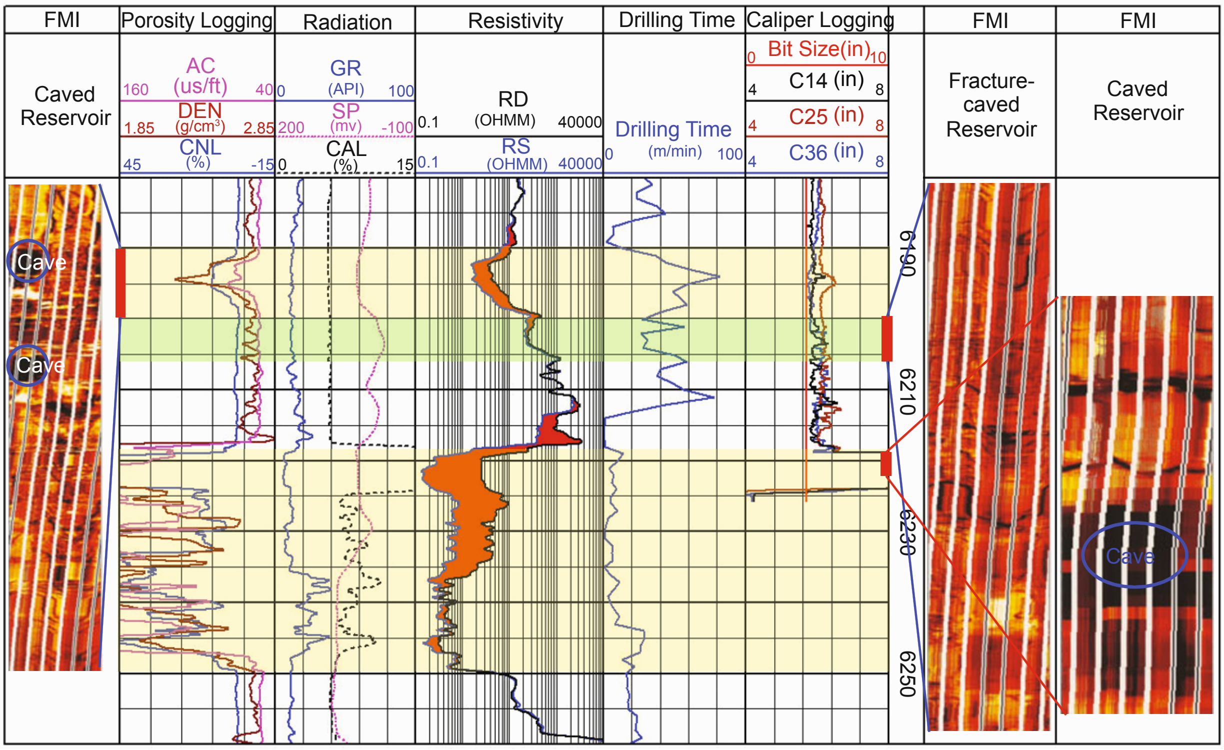

Fig. 3 Logging response of caved reservoir (6,191-6,199 m and 6,218.5-6,250 m) and fracture-caved reservoir (6,199-6,206 m) (taking Well LG35 as an example)

and selection of fracture indexes, calculation and reliability evaluation of fracture probability and computation of comprehensive fracture probability. Fu et al (2006b) identified the reservoir types using conventional logging data and FMI data. Qi et al (2006) performed logging characterization and quantitative calculation of reservoir parameters for carbonate reservoirs based on FMI logging. Tang et al (2008) proposed that conventional log and FMI can be combined to perform qualitative analysis and quantitative evaluation for carbonate reservoirs. Some scholars suggested a comprehensive probability index method to identify fractured reservoirs (Zhao and Bu, 1994; Wu et al, 1995; Wang and Guo, 2002) while water layers are usually interpreted to be Class III reservoirs due to the lack of consideration of the effects of fluid. Additionally, Zhang et al (2003) argued to employ the coefficient-weighted method to classify reservoirs but the oil reservoir interval cannot be distinguished clearly.

Based on previous studies (Kazatchenko et al, 2007; Liu et al, 2009), logging information which is sensitive to fractures and caves is chosen to classify reservoirs in this paper. And we also introduce the factors reflecting matrix-porosity and cave-porosity and the parameters (thickness of fracture and cave) from FMI (see Table 1). Finally, the cross-plot of comprehensive probability index (CPI) against the permeability derived from logging interpretation is used to evaluate formations (shown in Fig. 4). Based on the cross-plot, the classification criteria are listed in Table 1 for carbonate reservoirs with different storage spaces.

Table 1 Weighted coefficient and grading criterion of logging information

Logging information	Weighted coefficient	Grading criterion				
		100 Score	75 Score	50 Score	25 Score	0 Score
Micro-laterolog	0.060	<10	10-50	50-100	100-200	>200
Dual lateral log	0.105	$(R_d\text{-}R_s)/R_d>0.5$	Score=$(R_d\text{-}R_s)/R_d\times200$			$R_d\geq1000$
Fracture thickness of FMI	0.134	Sinusoidal curve	—	—	—	No changing of FMI
Pore-cave thickness of FMI	0.196	Black or dark fringe with fair thickness	—	—	—	No changing of FMI
Dual caliper log	0.096	$D_1\text{-}D_2\geq2$	1.5-2	1-1.5	0.5-1.0	<0.5
Matrix porosity	0.097	Curve suddenly rising	—	Curve changing slightly	—	No changing of curve
Fracture porosity	0.102	Curve suddenly rising	—	Curve changing slightly	—	No changing of curve
Fracture permeability	0.099	Curve suddenly rising	—	Curve changing slightly	—	No changing of curve
Pore-cave thickness of dipole sonic log	0.111	Acute disturbance, V-form interference fringe	—	—	—	No changing of dipole sonic log

Twenty four unit-layers are selected as the key formations for the comprehensive probability index method from twelve oil-testing intervals of seven wells in the Lundong area. Based on the differences of various logging data reflecting reservoir parameters, the corresponding weighted coefficients are given. The optimum logging information is selected as follows:

1 Resistivity of the micro-laterolog: *RMLL*;

2 Resistivity of the dual laterolog: $(R_d\text{-}R_s)/R_d$;

3 FMI: estimating thickness of fracture zone (H_f) and cave zone (H_c);

4 Dual caliper log: $D_1\text{-}D_2$;

5 Porosity log: estimating matrix porosity (Φ_b), fracture porosity (Φ_f), fracture permeability (K_f);

6 Dipole acoustic variable density log: D_{fc}.

We should indicate that the method is more available for fractured carbonate reservoirs because the logging information selected here is more sensitive to fractures.

Calculation of weighted coefficients:

(1) Determine the parameter of reservoir reflection ability (P_i):

$$P_i=\sum_{j=1}^{24}(h_{ij}/H_j)\,(i=1,\ 2,\ \cdots,\ 9,\ \ j=1,\ 2,\ \cdots,\ 24) \quad (1)$$

(2) Normalization of weighted coefficients:

$$\overline{P}_i=P_i\Big/\sum_{t=1}^{n}P_t\ (i=1,\ 2,\ \cdots,\ 9) \quad (2)$$

where i is the label of the ith logging information, i=1, 2,…, 9; j denotes the label of the jth layer, j=1, 2, …, 24; h_{ij} is the thickness reflected from the ith logging information in the jth layer; H_j is the thickness of the jth layer; P_i is the reservoir reflection ability of the ith logging information; $\overline{P}_i$ is the normalized coefficient-weighted from the ith logging information. The weighted coefficient of various logging information above is listed in Table 1.

Calculation process of *CPI*:

(1) Logging response grading:

$$G_{ij} = \left(\sum_{j=1}^{24} a_i \cdot h_{ij} \right) \Big/ H_j \quad (i=1,\ 2,\ \cdots,\ 9) \tag{3}$$

(2) Calculation of *CPI*:

$$CPI_j = \sum_{i=1}^{9} (\overline{P}_i \times G_{ij}) \quad (j=1,\ 2,\ \cdots,\ 24) \tag{4}$$

where a_i is the score of the *i*th logging information; G_{ij} is the score of the *i*th logging information in the *j*th layer; CPI_i is the comprehensive probability index of the *j*th layer.

Finally, the classification criterion of reservoir types in the Lundong area is established as shown in Table 2. To obtain better results, permeability from logging interpretation is also introduced to make a cross-plot with *CPI* as shown in Fig. 4. According to the different range of *CPI* (e.g., 48, 25 and 10, respectively), the reservoirs can be classified into three types: Class-I reservoir, Class-II reservoir, and Class-III reservoir. The corresponding permeability for the three types of reservoirs is 10 MD, 1 MD and 0.01 MD respectively.

For Table 2, it should be noted that if comprehensive probability index is greater than 25% and permeability is greater than $1\times10^{-3}\mu m^2$, a gas-production well can have intermediate deliverability. As for an oil-production well, the permeability should be greater than $1\times10^{-2}\mu m^2$ in order to get the same deliverability.

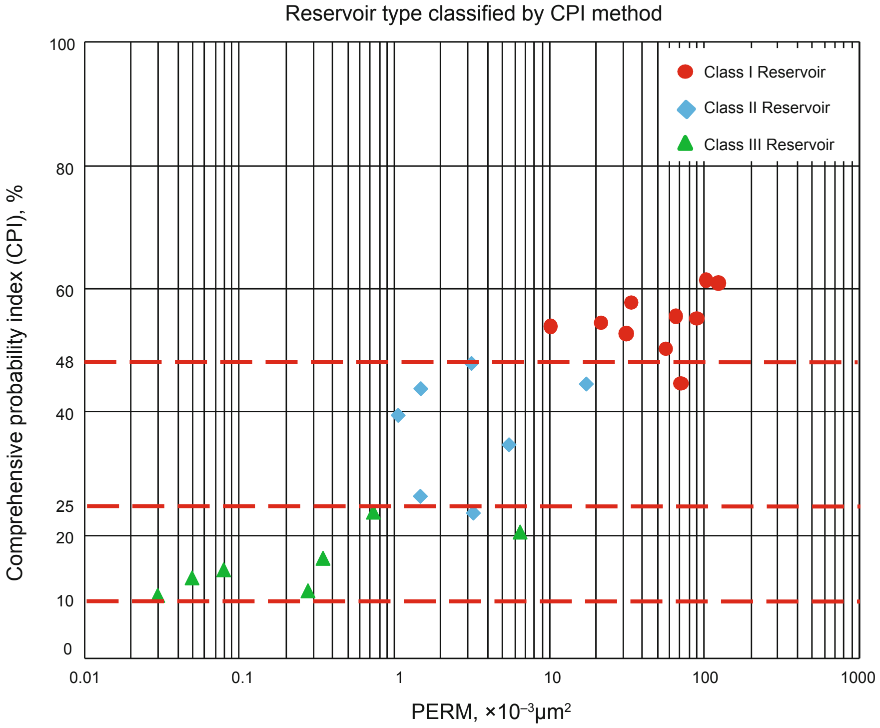

Fig. 4 Reservoir type classification by comprehensive probability index method in the Lundong area

Table 2 Classification criterion of reservoir type in the Lundong area

Reservoir hierarchy	*CPI* %	Permeability $\times10^{-3}\mu m^2$	Deliverability	Type of fractures and caves
Class I	>48	>10	Acid fracturing not needed to obtain industrial capacity	Pore-cave reservoir, high angle and network fracture, fracture-cave reservoir
Class II	25-48	1-10	Using acid fracturing can obtain industrial capacity	High angle fracture, diagonal fracture
Class III	10-25	0.01-1	Using acid fracturing can obtain little industrial capacity	Diagonal fracture, low angle fracture
Non-reservoir	<10	<0.01	Even acid fracturing will not enable any industrial output	—

4 Reservoir fluid identification

Reservoir fluid identification is a qualitative logging interpretation. It requires that an interpreter can quickly and directly identify reservoir fluids using logging and testing information. The multivariate step discriminant analysis method is employed to identify reservoir fluids here. In this method, variables with high discriminant ability are preserved in the discriminant function, while variables with low discriminant ability are eliminated, which means "some in and some out" (Tian et al, 2005; Hu et al, 2005; Duan et al, 2007).

4.1 Establishment of discriminant function

Firstly, three kinds of fluid saturated layers are defined here: gas layer, gas-water layer and water layer. Nine kinds of logging data including GR, SP, CAL, AC, CNL, DEN, RT, RXO and RMLL are chosen as variables. Then calibration and normalization are implemented over these logging data. Finally four kinds of logging data (AC, DEN, CNL and RT) with high contribution to fluid identification are selected.

According to logging data and testing data, the discriminant functions through multivariate step discriminant analysis method are established as follows:

Gas layer:

$$\text{Function1}=2.227\times GR-4.084\times SP+3.937\times CAL+1.961\times AC-0.366\times RT-2.313\times CNL-3.967$$

Gas-water layer:

$$\text{Function2}=-1.692\times GR-4.582\times SP-5.352\times CAL-2.451\times AC+0.753\times RT+2.468\times CNL-4.910$$

Water layer:

$$\text{Function3}=2.437\times GR-5.052\times SP-6.534\times CAL-3.634\times AC+0.719\times RT+4.285\times CNL-6.040$$

In the formula, ZAC, ZDEN, ZCNL and ZRT are the normalization results of AC, DEN, CNL and RT, respectively.

4.2 Validation of identification results

After substituting the samples into the discriminant function, the samples are reclassified by employing posterior probability. The results are compared with original sample types. The coincidence rate of gas layer, gas-water layer and water layer is 90.4%, 78.6% and 91.7%, respectively. The average coincidence rate is 87.2% as shown in Table 3. The high coincidence rates suggest that the multivariate step discriminant analysis method is a feasible and practical technique for fluid identification.

Table 3 Identification results of reservoir fluids

	Testing results	Predicted group membership			Total
		Gas	Gas-water	Water	
Count	Gas	914	31	66	1011
	Gas-water	23	396	85	504
	Water	0	20	221	241
Coincidence rate, %	Gas	90.4	3.1	6.5	100.0
	Gas-water	4.6	78.6	16.9	100.0
	Water	0.0	8.3	91.7	100.0

5 Comprehensive formation evaluations

After the reservoir classification and fluid identification, the reservoir production capability can be estimated, and then it should be decided whether any engineering strategies such as acid fracturing are needed. Finally, a comprehensive reservoir evaluation can be carried out.

The comprehensive probability index (CPI) method is used to interpret and predict well LG36 as an example (Fig. 5). The *CPI* of the interval of 5,942 m to 5,950 m is more than 48%, so it can be classified as a Class-I reservoir. For the interval of 5,950 m to 5,958 m, *CPI* ranges from 25% to 48%, so it is classified as a Class-II reservoir. The oil-testing results show that the gas-production capacity of the interval of 5,940 m to 5,960 m is 99,056 m^3 to 104,652 m^3 after perforation and acid fracturing, showing that our evaluation result is reasonable. Meanwhile, it also shows that the comprehensive formation evaluation method is valid and effective for classifying reservoirs. Using the method described above, the reservoir from 5,976.5 m to 5,980.5 m is evaluated to be a Class-II reservoir.

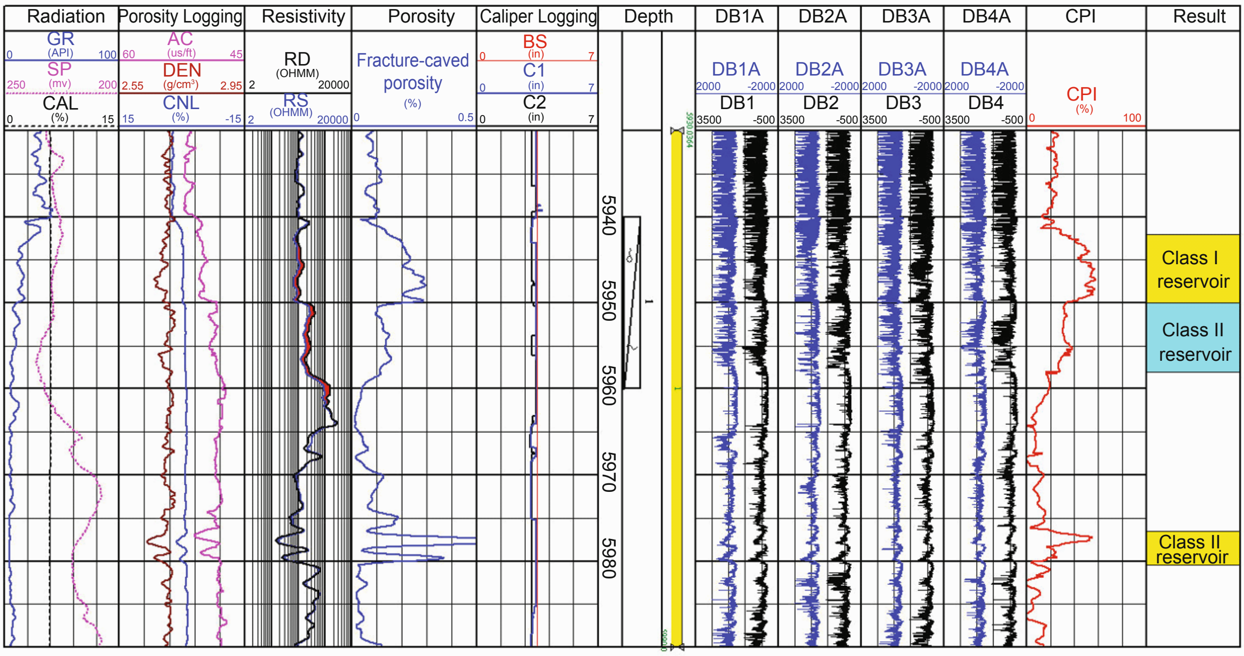

Fig. 5 Result of formation evaluation for well LG36 (5930 m-5990 m)

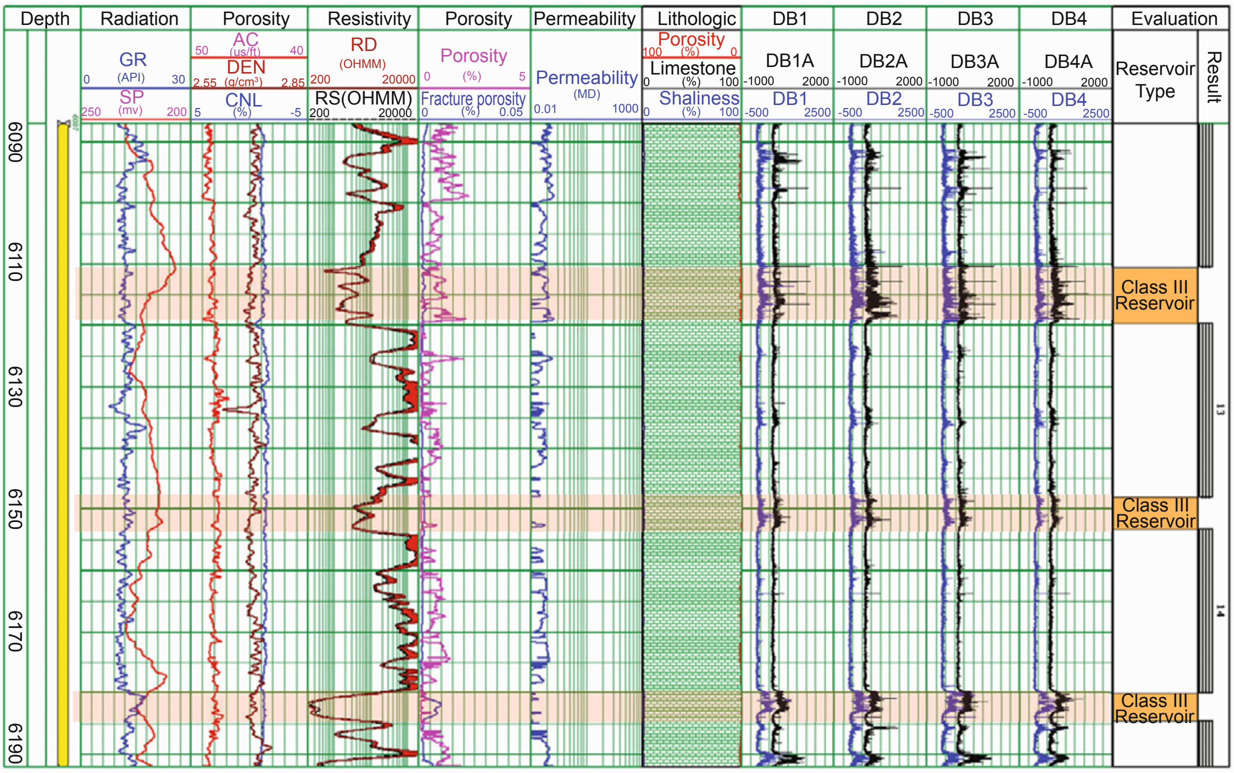

Fig. 6 Comparison of formation evaluation results by comprehensive probability index method for well LG36

As shown in Fig. 6, non-reservoir is interpreted previously by other evaluation methods while through our comprehensive evaluation it is classified into Class III reservoir, which has deliverability if artificial acid fracturing treatment is implemented.

6 Discussion: evaluating reservoir quality based on pore type inversion results

Wang et al (2011) realized the inversion of secondary pore types by reversely employing their proposed velocity prediction method. And three kinds of main secondary storage space types including cracks, caves, and needles (holes) can be obtained via this method. This paper is not aimed at interpreting how to invert pore types but focused on evaluating reservoir types based on pore type inversion results.

The key idea of the formation evaluation method is integrating the inverted pore types and their corresponding porosities to indicate valid reservoirs. The respective porosity of each kind of pore (Por_Crack, Por_Cave, and Por_Needle) can be obtained by multiplying the inverted proportions of pores with total porosity. Generally when there are cracks only, due to the small pore space and the limitation of fluid storage ability, favorable reservoirs often cannot be formed. And when there are caves only but no cracks, the developed caves are isolated one by one, so the transportation ability of fluids is also limited and reservoirs with high industrial production are not easy to form. Therefore, we need to seek valid reservoirs according to the principle that needles and caves develop (ensuring high porosity), and the communicative fractures also develop (ensuring high permeability).

Based on the principle above, and in combination with the actual situation in the study area, an effective reservoir type classification criterion is established as follows (Table 4): (a) High-quality reservoir: total porosity is higher than 3%, and the pore type is dominated by dissolved caves or holes, and it also has a certain number of cracks (Por_Crack≥0.1%); (b) Poor reservoir: total porosity is in the range of 1%-3%, and the pore type is dominated by dissolved caves or holes, and it also has a certain number of cracks (Por_Crack≥0.1%); (c) Dry reservoir: Even if the porosity of the reservoir is high while only caves are developed and there are no holes or cracks (that is to say, the porosity of cracks and holes are less than 0.1%); (d) Non-reservoir: total porosity is less than 1%.

Table 4 Reservoir type classification criterion based on pore type inversion for carbonate reservoirs in the Tarim Basin

Reservoir type	Total porosity	Holes or caves	Crack porosity
High-quality reservoir	>3%	Dominated	≥0.1%
Poor reservoir	1%-3%	Dominated	≥0.1%
Dry reservoir	—	Only caves	<0.1%
Non-reservoir	<1%	—	—

Fig. 7 shows the pore type inversion results (4th column) and the computational corresponding porosities (6th column) of each kind of pores for a well in the Tarim Basin. In the figure, the left two columns are the standardized logging data, and the third column is the lithology analysis result. In the fifth column, Por_Total denotes the total porosity of the reservoir, and Por_Critical denotes the critical porosity

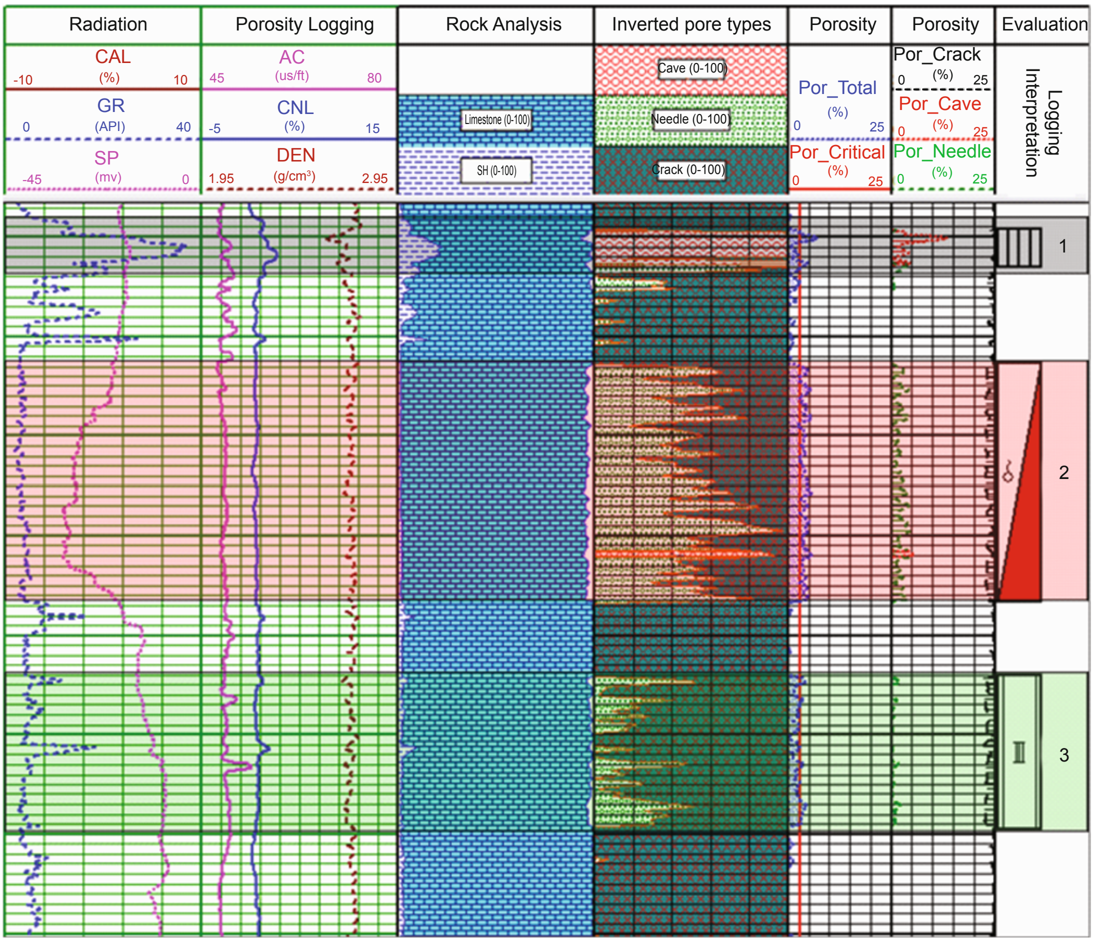

Fig. 7 Integration of pore type inversion results and the computational corresponding porosities to evaluate the quality of the reservoir intervals

to classify the reservoir type. The last column is the logging interpretation result.

Based on the reservoir type classification criterion, three sets of reservoirs can be easily differentiated from non-reservoirs (Por_Total is less than Por_Critical in 5th column). For the first set of reservoirs, although the total porosity is greater than 3%, only the cave-shaped pores are developed (both Por_Needle and Por_Crack are nearly zero in 6th column). In this situation, the permeability of reservoir must be very low, which is not favorable to the migration of fluids. Therefore, the reservoir is classified as an invalid reservoir or dry reservoir, which accords with the logging interpretation result in 7th column. For the second set of reservoirs, the total porosity (Por_Total) is bigger than critical porosity (3%) and holes, cracks, and caves are developed (shown in the 6th column). Therefore, according to the criteria of reservoir type classification established above, this reservoir is evaluated as a high-quality reservoir, which is also consistent with the logging interpretation results. For the third set of reservoirs, the total porosity (Por_Total) is near to 3%, so the storage capability is more or less inferior. However because of the development of cracks and holes (shown in 6th column), the reservoir still has favorable permeable ability. Considering both the storage capability and the permeability, this reservoir is evaluated as a poor reservoir according to the classification criteria above. Compared with the Class III testing results, the evaluated result is also reasonable.

To sum up, it is feasible to integrate the pore type inversion results and the corresponding porosities of different secondary pores to evaluate the quality of complex carbonate reservoirs with various secondary pores, and the evaluation results are shown to be reasonable. Though the criteria of reservoir evaluation still need to be modified by using more different actual cases, the comprehensive reservoir evaluation method based on the reservoir pore type and the size of porosity is economical and practicable.

7 Conclusions

1) Based on multiple logging data and interpretation results, the comprehensive probability index (CPI) method is used to predict reservoirs, which decreases the dependence on the log quality and uncertain geological factors, and avoids the limitation of individual logging data. Application of this method to the Lundong area shows favorable results. In this paper, the reservoirs are classified into four types Class-I reservoir, Class-II reservoir, Class-III reservoir and non-reservoir by using the CPI method. The average coincidence rate reaches 90%. Additionally, some intervals which are previously interpreted to be non-reservoir by other methods are interpreted to be Class III reservoir here.

2) Reservoir fluids are identified by using the multivariate step discriminant analysis method, and the coincidence rate reaches 91.4%, proving this method to be feasible and practical for reservoir fluid identification.

3) Based on the pore type inversion results, respective porosity of different pores can be calculated by multiplying the proportions with total porosity. The integration of these porosities and inverted pore types is an economical and practical reference method to evaluate the quality of carbonate reservoirs.

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