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Types of Diagenetic Facies of Tight Sandstone Reservoir and Its Quantitative Identification by Well Log Data

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Abstract: According to the features of clastic mineral components, diagenesis, diagenetic mineral combination, etc., the tight sandstone reservoir of Es_3x^1 in block Zhuang62-66 is classified into 5 types of diagenetic facies by the analysis of thin sections, casting thin sections, scanning electron microscopy and core description. Natural gamma (GR), true formation resistivity (Rt), flushed zone formation resistivity (Rxo), compensated neutron (CNL), density (DEN), acoustic (AC) and spontaneous potential (SP) are selected on the basis of comprehensively analyzing the log response mechanism of different diagenesis. The effective log recognition model of diagenetic facies is established on the basis of principal component analysis, five comprehensive variables F_1~F_5 are built, while F_1 and F_2 account for 91.4% of the total variance, which could replace primitive multi-dimension information. The method is verified through processing of coring wells, thus providing a geological basis for the high quality reservoir prediction of the oilfield in the future.

Keywords: Diagenetic facies, diagenesis, quantitative identification by well log data, principal component analysis.

1. INTRODUCTION

Tight sandstone reservoirs often experience complex diagenesis, especially those which are adverse to pore preservation, such as compaction, cementation, etc. As a comprehensive performance of reflecting diagenetic products of specific diagenetic environments or processes, diagenetic facies obviously controls petrophysical properties of reservoirs [1-5]. Diagenetic facies analysis is to establish a genetic relationship between diagenesis and the evolution characteristics of reservoir petrophysical properties, and to clarify the combination types and distribution characteristics of diagenetic facies, and their effect on petrophysical properties of reservoirs, thus providing the theoretical basis for summarizing the characteristics of development of reservoirs in transverse and longitudinal sections [6-14]. In recent years, through studies on diagenetic facies, many experts and scholars suggested that, as a key controlling factor of the development of high quality reservoirs, distribution of diagenetic facies is a vital guidance for the exploration of “dessert” reservoirs against the background of low permeability-tight reservoirs especially [15, 16].

Currently, diagenetic facies research mainly relies on the data of cores and thin sections from coring wells, while drilling cores can not be applied to the continuous division of diagenetic facies due to high cost and its limited number. As wirelone logging can provide a lot of information about petrophysical properties, logging data has unique advantages in terms of data quality, resolution, continuity, economic cost, etc. A lot of research of utilizing log information to classify reservoir diagenetic facies has been done [16-20]. The key is to summarize the log response characteristics of different diagenetic facies with the guidance of logging geology and other related disciplines and to establish the corresponding model and criterion of log recognition based on the mathematical statistics, finishing the recognition of types of diagenetic facies except for coring intervals. On the basis of previous studies, the author took tight sandstone reservoir of Es_3x^1 in block Zhuang 62-66 as an example. On the basis of research on the characteristics of diagenetic facies, effective log discrimination standard of diagenetic facies is established based on the principal component analysis. Qualification rate of correction of core samples is over 85%, providing a geological basis for exploration and development of the oilfield in the next step.

2. CHARACTERISTICS OF DIAGENESIS AND DIAGENETIC FACIES

2.1. Analysis of Diagenesis and its Log Response Mechanism

2.1.1. Compaction

The content of cuttings, matrix and other plastic grains of reservoir of Es_3x^1 in block Zhuang62-66 is so high that the formation has poor anti-pressure ability. Pores are easily destroyed due to compaction. Common compaction phenomena (Fig. (**1a**), Fig. (**1b**)) include: linear-concave convex contact of clastic particles; compressional deformation, distortion and pseudomatrixization of mudstones, shale cuttings, shale matrix, micas and other plastic grains; wavy extinction or even crushed or fractured of quartzs, feldspars

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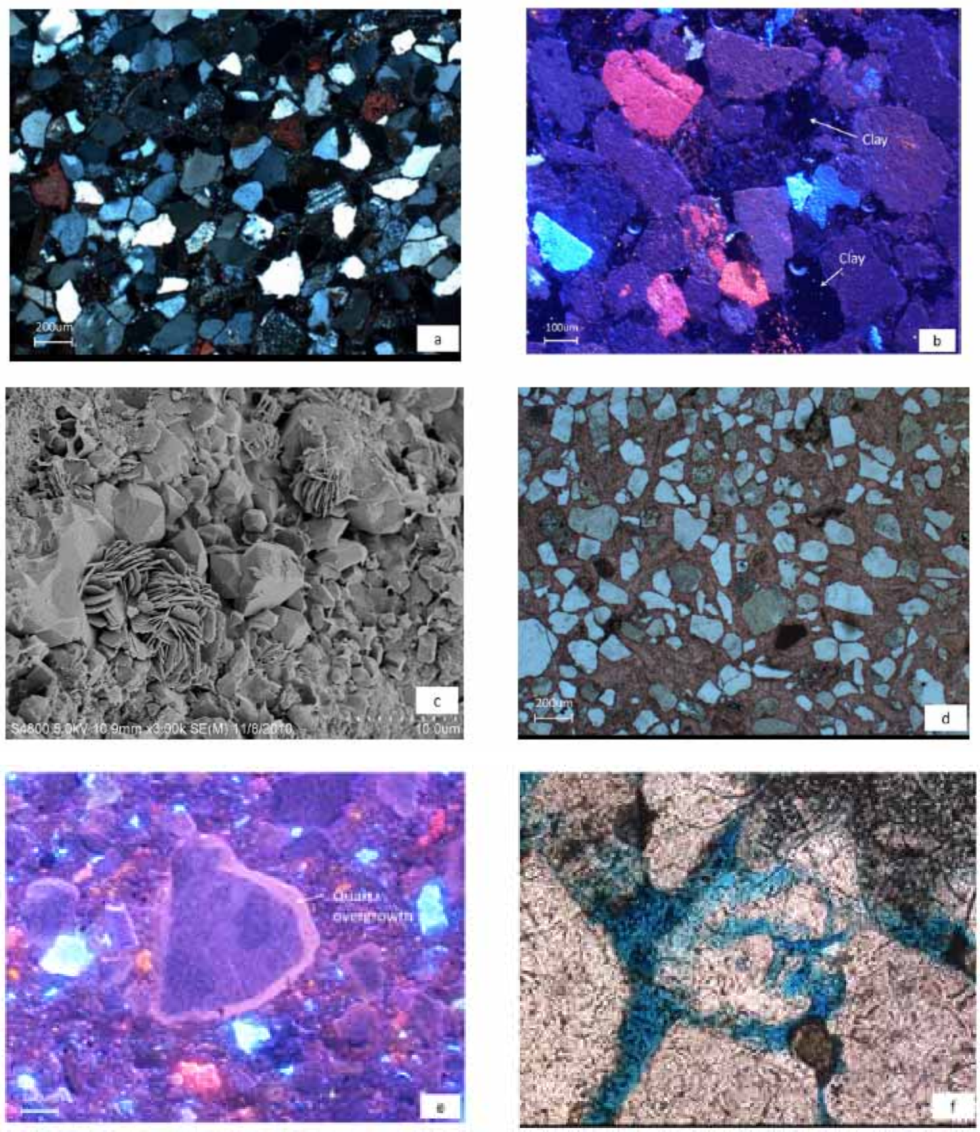

Fig. (1). Micro-image characteristics of tight sandstone reservoir of Es_3x^1 in block Zhuang 62-66 in Wuhaozhuang Oilfield. (**a**) Zhuang62, 3108.63m relatively uniform in particle distribution, intensive compaction, fractured rigid particles and directionally arranged plastic grains, intergranularly interstitial material is mainly sheet clay matrix(orthogonal light); (**b**) Zhuang66-1, 3452.45m clay mineral is mainly intergranularly interstitial material with a content of 5%-25% generally, according to x-ray diffraction, the main component is kaolinite, illite and chlorite, mixed-layer clay minerals (cathode luminescence); (**c**) Zhuang62, 3128.69m booklet kaolinite filling of intergranular pores(scanning electron microscope); (**d**) Zhuang 66-1, 3404.7m mainly fine sand, the main component is quartz, feldspar and volcanic debris, lots of crystal granular calcite filling of base cementation(orthogonal light); (**e**) Zhuang66-12-12, 3198.4m irregular quartz overgrowth, quartz edge is 0.03-0.06mm, mosaic contact between quartz grains(cathode luminescence); (**f**) Zhuang66-1, 3448.75m zigzag and wreck edge dissolution of feldspar grains(plane-polarized light).

and other rigid particles. In general, compaction leads to lower value of AC, higher value of DEN, lower value of CNL, and smaller magnitude difference of SP.

2.1.2. Cementation

Cementation of reservoir of Es_3x^1 in block Zhuang 62-66 is mainly clay mineral cementation, carbonate cementation and siliceous cementation. Cementation is mainly authigenic clay mineral cementation, followed by carbonate cementation and then siliceous cementation. In general, cementation leads to overall deterioration of petrophysical properties, while different types of cementation have different log response mechanisms.

Clay mineral cementation is mainly kaolinite cementation, followed by illite and illite/smectite mixed layer cementation (Table **1**). Authigenic clay minerals filling of intergranular pores leads to complicated reservoir pore structure (Fig. (**1c**)). Film-like or pore-lining produced clay minerals result in clogged pore throats, greatly reducing the effective porosity of reservoirs. Clay mineral cementation generally results in GR increasing, AC increasing, Rt decreasing and DEN increasing.

It is rich in carbonate cements and has multiple types, indicating obvious characteristics of multiple stages. According to the generation, cementation and interpenetration

Table 1. Content of clay minerals of tight sandstone reservoir of Es_3x^1 in block Zhuang 62-66.

Well number	Depth (m)	Relative content of clay minerals (%)				Ratio of I/S
		Illite/smectite mixed layer	Illite	Kaolinite	Chlorite	
Zhuang52-1	3210	18	8	64	10	20
	3214	15	15	59	11	20
Zhuang50	3215	34	60	5	1	15
	3225	33	39	24	4	15
	3239	21	31	44	4	20
	3251	10	24	58	8	15
	3256	38	39	23	——	15
	3260	25	37	28	13	20
Average		24.3	31.6	38.1	7.3	17.5

relationship of authigenic minerals, cementation types include calcite, dolomite and other early cementation and ferrocalcite, ferrodolomite and other late cementation. Early and late period of cements have different features and effects on petrophysical properties (Fig. (**1d**)). Carbonate cementation is the most important factor leading to tight reservoirs which are generally characterized by low value of AC, high value of DEN, low value of CNL, medium-high value of Rt, low value of GR.

It is relatively low in siliceous cements. The most common siliceous cementation is quartz overgrowth and authigenic quartz grain filling pores (Fig. (**1e**)), which are mainly produced by pressure solution and silicon released in transformation from feldspar to kaolinite. Siliceous cementation results in contact forms from point contact to suture line and surface contact, resulting in deterioration of reservoir petrophysical properties and shortened acoustic propagation path, so AC cannot fully reflect intergranular pores [17]. The reservoirs are generally characterized by AC decreasing, DEN increasing, Rt increasing.

2.1.3. Dissolution

Dissolution is a key factor in the development of secondary pores and it improves reservoir petrophysical properties. Dissolution of unstable components increases rock maturity (Fig. (**1f**)) and improves reservoir petrophysical properties as well. Reservoirs with development of dissolution are characterized by medium-high value of AC, low value of DEN, high value of CNL and low value of GR.

2.2. Classification and Characteristics of Diagenetic Facies

Based on the data of thin sections, casting thin sections, scanning electron microscopy, etc. and the comprehensive consideration of effect of diagenesis on petrophysical properties, combining with the analytical data of conventional petrophysical properties, reservoir of Es_3x^1 in block Zhuang 62-66 is divided into 5 kinds of diagenetic facies and the characteristics of each diagenetic facies are summarized as follows.

2.2.1. Compaction-matrix Filling and Tightness

Lithology of this diagenetic facies is relatively fine. Contents of mudstones and shale cuttings, clay matrix, micas, phyllites, slates, etc. are relatively high. The soft component is strongly deformed during compaction, leading to a sharp decrease of primary pores. Quartz overgrowth resulted from the pressure solution of late rigid particles and the filling of authigenic clay minerals and calcareous cements further reduce reservoir porosity. Reservoir pores are mainly compaction residual intergranular pores, a few dissolution pores and intercrystalline micropores. Reservoir petrophysical properties are poor. Porosity is 2.4%~9.8%, and permeability is 0.1 ~ 2.3mD.

2.2.2. Authigenic Clay Minerals Filling and Cementation

According to X-ray diffraction data (Table **1**), authigenic clay mineral of Es_3x^1 in block Zhuang 62-66 is mainly kaolinite, followed by illite and illite/smectite mixed layer, content of chlorite is relatively low. The average content of kaolinite is 38.1%, which fills pores in the form of vermicular and booklet aggregate. Although it provides some intergranular pores, its growth fills pore throats and formed tiny intergranular pores leads to the invalid pores increases and poorer permeability; the average content of illite is 31.6% which generally exists on particle surface or fills in pores, occupying pore space and clogging throats. Reservoir pores are mainly residual intergranular pores and intercrystalline micropores. Reservoir petrophysical properties are poor. Porosity is 4.9%~13.6%, and permeability is 0.15mD ~ 20.6mD.

2.2.3. Unstable Components Dissolution

According to the analysis of thin sections, dissolution of Es_3x^1 in block Zhuang 62-66 mainly occurs in feldspars, cutting grains, carbonate cements and clay matrix. Reservoir space of unstable components dissolution diagenetic facies includes: a certain number of dissolved pores sticking grains produced by the dissolution of clay cladding formed on the edges of mineral grains in early diagenesis stage; lots of honeycomb or irregular intragranular dissolved pores formed by corrosion of underground fluid along the fracture plane of the cleavage surface of feldspar; intragranular dissolved pores of dentate edges formed by corrosion of edges of grains. Reservoir petrophysical properties are the best. Porosity is 9.1%~23.2%, and permeability is 3.5mD ~ 31.2mD.

2.2.4. Quartz Overgrowth

Siliceous cementation is relatively common in Es_3x^1 reservoir with a relatively low content, the average content of siliceous cement is about 2%. Quartz overgrowth often occurs in clastic reservoirs with fewer matrixes and better sorting, and often accompanied by corrosion of feldspar. Chemical changes occur in feldspar under the appropriate PH value (acid medium provided by organic acids) and generates kaolinite and K^+, Al^{3+} and SiO_2 as well. This reaction provides certain material sources for quartz overgrowth (SiO_2). Quartz overgrowth fills in intergranular pores and changes reservoir pore structure, resulting in deterioration of reservoir petrophysical properties. Porosity is 7.1%~15.8%, and permeability is 0.64mD~10.6mD.

2.2.5. Carbonate Cementation and Tightness

According to the degree of cementation, ferrocalcite cementation, with mostly microcrystalline-fine crystalline structure, is divided into complete filling and partial filling. Ferroan calcite, ferruginous dolomite and other late carbonate cements are mostly semi-crystalline or filling cementation whose obvious plugging pore effect shows that the diagenetic environment gradually evolves to the alkaline environment due to the continuous consumption of acidic fluids. A large amount of ferroan calcites, ferruginous dolomite and other iron-bearing carbonates generated in the process decreases the reservoir petrophysical properties [21]. Reservoir petrophysical properties are the worst with only a few compaction residual intergranular pores and intercrystalline micropores. Porosity is 1.8%~7.3%, and permeability is 0.04mD~2.55mD.

3. QUANTITATIVE LOG RECOGNITION OF DIAGENETIC FACIES BASED ON PRINCIPAL COMPONENT ANALYSIS

3.1. Principle of Principal Component Analysis

High-dimensional arrays are often encountered in data processing. It is difficult to grasp the main information due to high dimensions, multi variables and correlation among variables. In order to analyze these multivariate data, dimensionality must be reduced properly [22-24]. Principal component analysis is a method of data dimensionality reduction, which reflects the hidden structure of the best explanatory variables of the data to a certain extent. Using the projection method to project the high-dimensional data onto low-dimensional space with the least possible loss of information, the aim of simplifying data structures from data dimension reduction is achieved.

The basic idea of principal component analysis is as follows. Set P-dimensional random vector $X = (x_1, x_2 \cdots x_p)^T$. Its mean vector is u and covariance matrix is V. Reconstitute the feature vectors $x_1, x_2 \cdots x_p$ into several unrelated variables $y_1, y_2 \cdots y_m (m < p)$ as little as possible and make sure they can fully reflect information reflected by the original P feature vectors.

Steps to get the n-dimensional observation sample matrix X of the P feature vectors are as follows.

$$X = \begin{bmatrix} x_{11} & x_{12} & & x_{1p} \\ & & \cdots & \\ x_{21} & x_{22} & & x_{2p} \\ & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{np} \end{bmatrix} \quad (1)$$

(1) Normalization of the raw data, i.e. the sample concentrated element x_{ik} is converted as follows:

$$x_{ik} = \frac{x_{ik} - \bar{x}_k}{S_k^2} \quad (i = 1, 2, \ldots.\ n;\ k = 1, 2, \ldots.\ p) \quad (2)$$

$$\bar{x}_k = \frac{1}{n}\sum_{i=1}^{n} x_{ik} \quad (3)$$

$$S_k^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_{ik} - \bar{x}_k)^2 \quad (4)$$

The obvious feature of principal component analysis is that every principal component depends on the scale of original variables measurement. When the scale varies, the eigenvalue λ is different. To overcome this difficulty, original variables are normalized as mentioned above to make the variance 1.

(2) Calculate the correlation coefficient matrix of the sample matrix:

$$R = \begin{bmatrix} r_{11} & r_{12} & & r_{1p} \\ & & \cdots & \\ r_{21} & r_{22} & & r_{2p} \\ & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{np} \end{bmatrix} \quad (5)$$

(3) Corresponding to the correlation coefficient matrix R, get P non-negative eigenvalues ($\lambda_1 > \lambda_2 > \cdots > \lambda_p \geq 0$) of the equation $|R - \lambda I| = 0$ with the Jacobi method. The corresponding feature vectors of the eigenvalue λ_i are as follows:

$$C^{(i)} = (C_1^{(i)}, C_2^{(i)}, \cdots C_p^{(i)}) \quad (6)$$

And meet:

$$C^{(i)}C^{(j)} = \sum_{k=1}^{p} C_k^{(i)} C_k^{(j)} = \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases} \quad (7)$$

(4) Select $m (m < p)$ principal components. When a

$$\left(a = \left(\sum_{i=1}^{m} \lambda_i\right) \Big/ \left(\sum_{i=1}^{p} \lambda_i\right) \right)$$

(m<P) is close to 1(for example $a \geq 0.9$), choose factors $y_1, y_2 \cdots y_m$ as the principal components corresponding to the $1, 2, \cdots, m$ principal component. The variance

of y_1, $y_2 \cdots y_m$ accounts for more than 90% of the total variance and basically reserved information of original factors ($x_1, x_2, \cdots, x_p$) and the number of factors is decreased from P to m , sifting factors.

3.2. Application of the Method

3.2.1. Characteristic Parameter Extraction

The key to log identification of diagenetic facies is parameters extracted from logging curves to reflect the characteristics of diagenetic facies. First, homing of depth of thin sections is achieved based on the contrast of the core natural gamma and the natural gamma curve with combination of core description. Diagenetic facies of 158 thin sections of 3 coring wells are named and sample layer data are extracted. Select 7 curves, i.e. GR, Rt, Rxo, CNL, DEN, AC and SP. The log response characteristics of sample layers corresponding to different diagenetic facies are shown in Table **2**.

3.2.2. Quantitative Log Recognition of Diagenetic Facies

Prior to the principal component analysis of sample data, standardization must be done to eliminate the difference of dimension and order of magnitude of parameters to avoid the system error of calculation results. Dimension and order of magnitude of sample data is in the same range, and then the correlation coefficient matrix is calculated based on the standardized data. Get the eigenvalue λ_i in the Jacobi method with the obtained correlation coefficient matrix R of sample data and corresponding unit feature vector and variance contribution (Table **3**).

The equation of principal component transform of tight sandstone reservoir of Es_3x^1 in block Zhuang 62-66 can be obtained from the feature vector corresponding to each eigenvalue:

$$F_1 = -0.45Rt + 0.39Rxo - 0.41GR + 0.5AC \\ -0.39CNL - 11.7DEN + 0.28SP \quad (8)$$

Table 2. Log response characteristics of different diagenetic facies of tight sandstone reservoir of Es_3x^1 in block Zhuang 62-66.

Diagenetic facies	GR	Rt	Rxo	CNL	DEN	AC	SP
	API	Ω•m	Ω•m	%	g/cm^3	us/ft	mV
Compaction-matrix filling and tightness	98.2	9.2	7.2	18.7	2.52	82.3	72.3
Carbonate cementation and tightness	61.1	53.4	51.9	5.4	2.48	59.2	65.4
Compaction-matrix filling and tightness	72.2	7.3	5.8	15.3	2.39	82.1	63.5
Authigenic clay minerals filling and cementation	95.6	8.4	8.2	15.4	2.46	84.6	45.3
Quartz overgrowth	115.6	16.6	15.6	16.2	2.52	82.6	68.2
Authigenic clay minerals filling and cementation	82.9	4.5	4.7	13.4	2.38	73.2	32.8
Unstable components dissolution	80.1	8.2	6.5	16.1	2.4	76.8	46.2
Carbonate cementation and tightness	72.5	62.2	60.8	12.5	2.62	70.4	80.2
Quartz overgrowth	90.4	13.8	11.9	12.3	2.45	71.3	62.3
Unstable components dissolution	93.2	18.7	15.8	23.6	2.43	86.3	60.3
Quartz overgrowth	76.7	6.2	6.5	8.6	2.39	64.5	36.5
Carbonate cementation and tightness	64.9	58.6	56.7	7.2	2.56	62.4	76.2
Authigenic clay minerals filling and cementation	120.2	11.9	10.9	22.3	2.59	93.5	69.1
Unstable components dissolution	72.9	5.4	4.1	12.7	2.32	70.3	40.2
Compaction-matrix filling and tightness	118.4	13.6	14.3	26.4	2.6	89.3	80.2

Table 3. Unit feature vectors, eigenvalues and variance contribution corresponding to eigenvalues.

Feature vector	Eigenvalue	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Variance contribution /%
F_1	2.68	-0.45	0.39	-0.41	0.5	-0.39	-11.7	0.28	53.6
F_2	1.89	0.32	0.98	-0.24	0.57	0.23	-0.63	-0.78	37.8
F_3	0.31	-0.16	0.32	-0.65	0.28	-0.44	-8.7	0.57	6.2
F_4	0.12	0.98	1.56	-0.09	0.83	0.56	-3.4	-0.64	2.3
F_5	0.05	0.8	0.67	-0.39	1.63	0.9	-2.4	-8.7	0.1

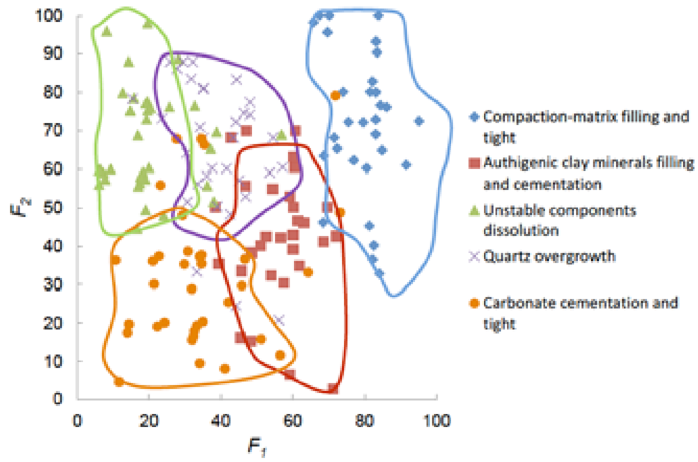

Fig. (2). Diagenetic facies recognition with the cross plot of principal components.

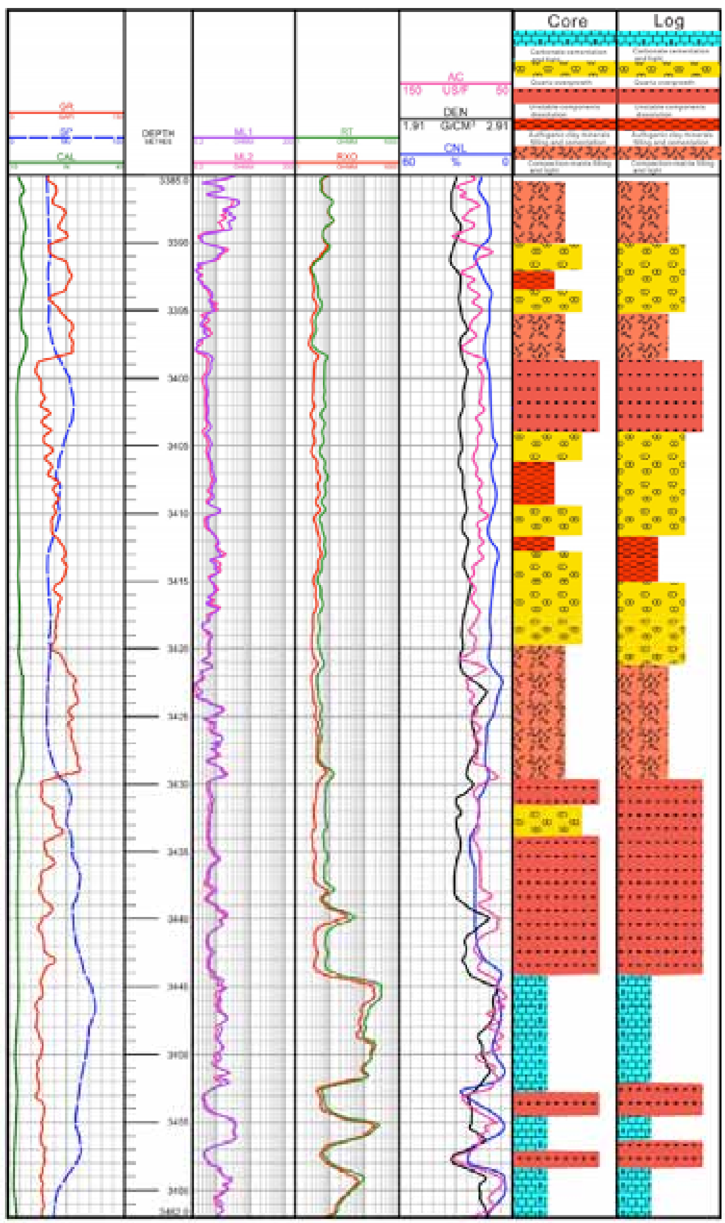

Fig. (3). Single well diagenetic facies recognition of tight sandstone reservoir of Es_3x^1 in block Zhuang 62-66.

$$F_2 = 0.32Rt + 0.98Rxo - 0.24GR + 0.57AC + 0.23CNL - 0.63DEN - 0.78SP \quad (9)$$

$$F_3 = -0.16Rt + 0.32Rxo - 0.65GR + 0.28AC - 0.44CNL - 8.7DEN + 0.57SP \quad (10)$$

$$F_4 = 0.98Rt + 1.56Rxo - 0.09GR + 0.83AC + 0.56CNL - 3.4DEN - 0.64SP \quad (11)$$

$$F_5 = 0.8Rt + 0.67Rxo - 0.39GR + 1.63AC + 0.9CNL - 2.4DEN - 0.87SP \quad (12)$$

Five calculation formulas of principal components can be obtained from the above formula, of which variance contribution of F_1 is the maximum, accounting for 53.6% of the total variance, while that of F_2 is 37.8%. F_1 and F_2 account for 91.4% of the total variance, indicating they can replace the original seven logs with small loss of effective data information. According to the principal component transformation model, principal component calculation of 198 thin section identification samples of the study area is calculated. Cross plot analysis of diagenetic facies with the most important principal components F_1 and F_2 has been done (Fig. (**2**)), according to the cross plot, 5 diagenetic facies can be effectively distinguished, qualification rate of correction of core samples is up to 86.4% through analysis of actual data of well Z66-1 in the study area (Fig. (**3**)).

CONCLUSION

(1) Based on the research of log response mechanism of diagenesis and according to the "core calibrating log" criteria, principal component analysis is employed to integrate a variety of logging information to principal component variables for highlighting characteristics of diagenetic facies, and continuously quantitative recognition of diagenetic facies of reservoir of Es_3x^1 in block Zhuang 62-66 is achieved. Compared with lab analysis results, coincidence rate is as high as 86.4%, verify the reliability of this method.

(2) Comprehensive analysis shows that selecting principal component variables to do crossplot whose cumulative variance contribution rate is greater than 90% could identify the diagenetic facies of reservior accurately, and solve the problem that direct use of logging crossplot variables could not identify diagenetic facies effectively.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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