

Article

Identification of Multi-Parameter Fluid in Igneous Rock Reservoir Logging—A Case Study of PL9-1 in Bohai Oilfield

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Abstract: Since the “13th Five-Year Plan”, the exploration of large-scale structural oil and gas reservoirs in the Bohai oilfield has become more complex, and the exploration of igneous oil and gas reservoirs has become the focus of current attention. At present, igneous rock reservoir fluid identification methods are mainly based on the evaluation method of logging single parameter construction, which is primarily a qualitative identification due to lithology, physical property, and engineering factors. Accurate acquisition of interference logging data, and multi-parameter coupling and recording coupling methods are few, lacking systematic and comprehensive evaluation and analysis of logging data. Since conventional logging data in the study area have difficulty accurately and quickly identifying reservoir fluid properties, a systematic analysis was conducted of three factors: lithology, physical properties, and engineering, as well as a variety of logging parameters (gas measurement, three-dimensional quantitative fluorescence, geochemical, FLAIR, etc.) that can reflect fluid properties were integrated. Based on parameter sensitivity analysis, the quantitative characterization index FI of multi-parameter coupling fluid identification was established using the data from testing, sampling, and laboratory testing to develop the identification standard. The sensitivity analysis and optimization of characteristic parameters were carried out by integrating the data reflecting fluid properties such as gas surveys, geochemical data, and related logging data. Combined with gas logging-derived parameters and improved engineering parameters (the value of alkanes released by rock cracking per unit volume C_{adjust} , C_1 abnormal multiple values, three-dimensional quantitative fluorescence correlation factor N), the fluid properties were identified, evaluation factors were constructed based on factor analysis, and fluid identification interactive charts were established. By analyzing test wells in the PL9-1 well area, the results of comparison test data are more reliable. Compared with conventional methods, this method reduces the dependence of a single parameter by synthesizing multiple parameters and reduces the influence of lithology, physical properties, and engineering parameters on fluid identification. It is more reasonable and practical. It can accurately and quickly identify the fluid properties of igneous rock reservoirs in the study area. It has a guiding significance for improving the accurate evaluation of logging data and increasing exploration benefits.

Keywords: Bohai Bay Basin; mesozoic igneous rock; fluid identification; comprehensive logging; PL9-1; FI; geochemical parameters



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1. Introduction

Since China discovered important igneous oil and gas reservoirs in the South China Sea basin, Songliao Basin, and Southwest Basin, etc., the exploration of igneous oil and gas reservoirs has attracted wide attention. Penglai 9-1 Oilfield (PL9-1) is located in the Bohai Bay Basin, China. Its coordinates are 38°12' N, 120°30' E, and it is a part of the Bohai Bay, China. It is relatively close to the coastlines of Liaoning and Shandong provinces in north China and has rich oil and gas reserves. Developed and managed by the China

National Offshore Oil Corporation (CNOOC), this oilfield is one of China's critical offshore oil and gas fields. The buried hill of Mesozoic igneous rock in the study area has better reservoir-forming conditions than other buried hills and has excellent exploration potential. In future oil and gas exploration and development, the buried hill of Mesozoic igneous rock will be an essential target area. Due to its wide distribution area, wide range, large thickness, good reservoir performance, superior cover conditions, favorable structural background, and various accumulation mechanisms, it has good accumulation conditions and excellent exploration potential.

This is mainly reflected in the following aspects: the wide distribution area of Mesozoic igneous buried hills means that there is a larger area for oil and gas exploration, increasing the possibility of discovering and developing multiple oil and gas fields and improving the overall exploration success. Its wide distribution range covers different geological units and sedimentary environments, provides the possibility of a variety of accumulation conditions and reservoir types, and can be explored in different areas and depths, thus improving the diversity and success rate of oil and gas exploration. Its large thickness means that it has a larger reservoir space, can provide a larger oil and gas storage space, and increases the reserves of oil and gas reservoirs, which is particularly important for developing the study area. The subsurface igneous rock has good reservoir performance; its porosity and permeability are relatively high, especially in volcanic and intrusive rock; the fractures are well developed, providing good reservoir space and flow channel for oil and gas. Good capping rock conditions accompany it, and the overlying sedimentary rock or mudstone layer can form an effective capping layer to ensure the stability and recoverable ability of the reservoir. It is located in the favorable tectonic fracture zone, which is conducive to accumulating and preserving oil and gas and forming efficient oil and gas reservoirs. In addition, the reservoir formation mechanism consists of various elements, including structural reservoirs, lithologic reservoirs, and fracture reservoirs. It makes exploration more flexible and successful, and different exploration and development strategies can be adopted according to geological conditions. With the development of exploration technology, seismic exploration, logging, and drilling technology, the exploration and development of igneous rock buried hills is more efficient and accurate. The exploration potential and development value of igneous buried hills are further improved.

The Bohai Bay Basin experienced two large-scale volcanic activities in the Mesozoic and Cenozoic, and the favorable igneous rock enrichment area is mainly located in the central and eastern Bohai Sea [1,2]. PL9-1 ancient, buried hill is a large oil field with weathering crust as a reservoir, located on the top of granite in the middle saddle of the buried hill to the northwest of Miao. The Jiaoliao Uplift in the Bohai Bay Basin is inserted into the east side of the Bozhong Depression to form a nose-shaped bulge (Figure 1a). The southeast side of the bulge is connected to the depression by faults. At the same time, the northern edge is defined by stratigraphic overlap lines [3] (Figure 1b). The existence of reservoir fractures leads to the phenomenon of leakage and gushing of drilling mud in the well, which makes the sample doped with other substances, thus making the collected sample inaccurate. Mud pollution interferes with the components of gas measurement parameters, and the fluid situation cannot be accurately identified [4], which increases the difficulty of logging interpretation. At the same time, the lithology classification and naming of igneous rocks in the study area are relatively complex and chaotic, which makes it difficult for the logging to accurately and quickly identify the lithology and needs more guidance for subsequent interpretation and evaluation. Affected by the lithology, the response characteristics of the conventional logging of the reservoir fluid properties in the Mesozoic buried hill are not prominent. Different lithologies' hardness, composition, and density lead to different permeability and porosity of different igneous rocks, making the reservoir physical properties of different igneous rocks different. The composition of the reservoir space is very complex, which makes the reservoir fluid properties more difficult to identify. In addition, the influence of engineering parameters also reduces the

interpretation and data accuracy of conventional logging methods. This intensifies the interference in the accurate identification of oil and gas reservoirs.

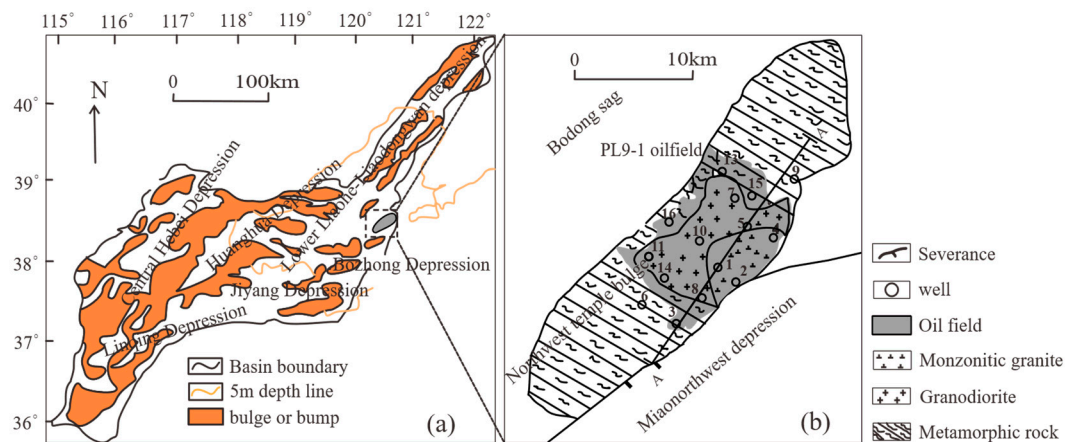


Figure 1. Regional geological survey of Penglai 9-1 oilfield (PL9-1) in Bohai Bay Basin. (a) Study area location; (b) Lithology, reservoir, and well location distribution in the study area.

Therefore, the method proposed in this paper is to systematically analyze the lithology, physical properties, and engineering factors and synthesize a variety of logging parameters (gas measurement, three-dimensional quantitative fluorescence, geochemical, FLAIR, etc.) reflecting the fluid properties. Based on the sensitivity analysis of parameters, it is difficult for conventional logging data in the study area to accurately and quickly identify the fluid properties. The quantitative characterization index FI of multi-parameter coupling fluid identification was constructed by using the data of testing, sampling, and laboratory testing to establish the corresponding identification criteria, and the sensitivity analysis and optimization of characteristic parameters were carried out by integrating the logging data and related logging data reflecting fluid properties such as a gas survey and geochemical data. Combined with gas logging-derived parameters and improved engineering parameters (value of alkanes released by rock cracking per unit volume C_{adjust} , C_1 abnormal multiple values, and three-dimensional quantitative fluorescence correlation factor N), evaluation criteria were established to identify fluid properties, and evaluation factors were constructed based on factor analysis to develop fluid identification interactive charts. Analyzing test wells in the PL9-1 well area and comparing test data verified that the evaluation results were more accurate. Moreover, the method is less affected by lithology, physical properties, and engineering parameters. By integrating multiple parameters, the uncertainty and error of a single parameter are reduced, and the influence of lithology, physical properties, and engineering parameters on fluid identification is reduced. Therefore, the rapid identification of fluid properties of igneous rock reservoirs in the study area can be carried out, which has guiding significance for improving the accurate evaluation of logging data and increasing exploration benefits. It also helps guide the subsequent development of the PL9-1 block reservoir. It can additionally improve the accuracy and reliability of fluid identification in unconventional reservoirs, optimize reservoir evaluation and development designs, and optimize drilling and horizontal fracturing designs.

2. Analysis of Influencing Factors of Fluid Identification

The reservoir space of the Mesozoic buried hill is complex and mainly composed of highly heterogeneous pores and fractures, which influence the rock mechanics, ground stress, and mineral composition. The lithology composition is complex, and the longitudinal change is fast under the influence of intense volcanic activity, volcanic eruption, and silence, constituting the periodic change in volcanic activity. The large scale of activity and short eruption time are accompanied by the co-development of various volcanic eruption minerals, forming volcanic rocks such as andesite, dacite, and volcanic breccia [5]. The study

area is dominated by metamorphic rocks and granites, mostly light red and gray-white. Its structure mainly has two kinds of medium, coarse-grained and fine-grained, blocky structures. The main mineral composition is primarily quartz, potassium, and plagioclase, while the secondary minerals are mica and hornblende, accompanied by a small amount of pyroxene. Currently, the lithology classification and naming of igneous rocks in the study area are relatively complicated and confusing, and the logging technology makes it difficult to accurately and quickly identify the lithology. The guidance for subsequent interpretation and evaluation needs to be revised. The response characteristics of conventional logging of reservoir fluid properties in Mesozoic buried hills are obscured (Figure 2), so it is urgent to develop fluid identification technology methods and technical processes.

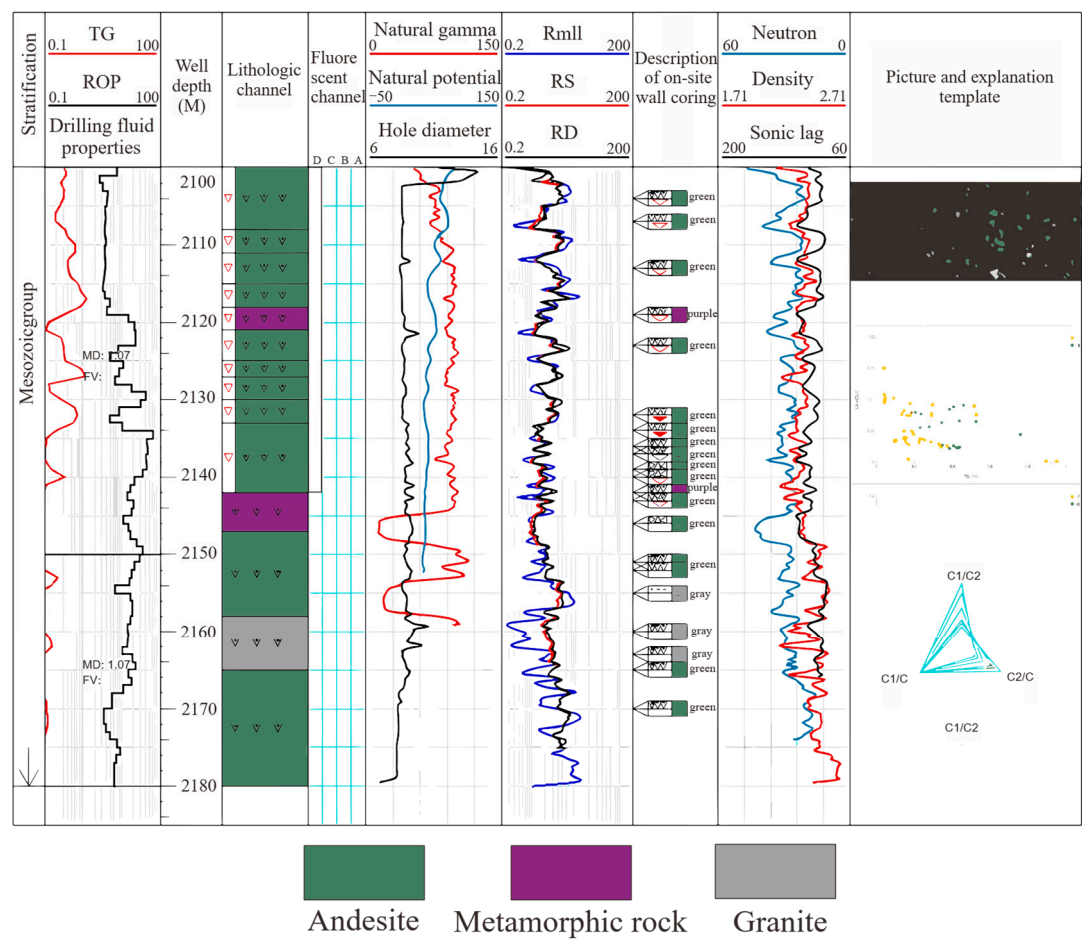


Figure 2. PL9–1–1 well-buried hill oil and gas display.

Primary pores, such as almond pores, are common in the rock structure of the study area. Secondary pores include intracrystalline dissolution pores, intracrystalline dissolution pores, and crypto explosion rock juice dissolution pores. In addition, explosion and dissolution fractures also exist, constituting the reservoir space of igneous rocks. The reservoir space of the Mesozoic buried hill is affected by many factors, such as lithology, cyclic interface, crypto-explosive fissure formation, weathering degree, etc. In addition, reservoir space types are diverse, the structure is complex, and significant differences exist between the logging response and oil and gas productivity. The adequate reservoir space of an eruptive rock reservoir is mainly composed of unfilled fractures, solution holes, and solution fractures. In general, it presents the characteristics of a fracture-porosity reservoir. The hardness, composition, and density of different lithologies lead to different permeability and porosity of various igneous rocks, which renders the reservoir physical properties

of other types of igneous rocks different and the composition of the reservoir space very complicated, making it more challenging to identify the reservoir fluid properties [6].

In addition, an excessive drilling speed in drilling engineering may cause cuttings to fail to return to the surface in time, affecting the accuracy and timeliness of logging data and thus interfering with identifying formation fluids. Wall collapse or borehole enlargement may result in mixing drilling fluid with formation fluids, and changes in drilling fluid properties (e.g., density, viscosity, fluid loss, etc.) may affect the collection and interpretation of logging data. Frequent well-washing operations may interfere with the natural state of formation fluids. Different types of bits and the degree of bit wear may affect the shape of cuttings and the interpretation of logging data. Formation fluids can mix, especially in the case of wellbore instability, affecting the accurate identification of a single oil and gas reservoir. The function of each parameter and other factors will affect the accuracy of logging data and the identification of reservoir fluid properties by conventional logging. In exploration and development, there are abnormal pressure systems in the Mesozoic, and the internal reservoir fractures are highly developed, which brings significant challenges to the risk of drilling engineering. The occurrence of well loss and kick will reduce the reliability of well logging data. Losses and kicks can be effectively prevented and reduced by optimizing drilling technology, adjusting on-site plugging technology, improving the formulation of plugging agent, adding different drilling fluids, monitoring surface or bottom hole parameters based on sensors, developing a complex, intelligent drill pipe, and building models based on artificial intelligence and machine learning [7,8]. Although losses and kicks can be reduced by optimizing drilling techniques, adjusting on-site plugging techniques, improving the formulation of plugging agents, and adding different drilling fluids, these measures may introduce new interference factors that affect the interpretation accuracy and data accuracy of conventional logging methods, thus affecting the accuracy of identification. These interference factors include changes in the mud properties, wellbore conditions, residual plugging materials, and chemical reactions of different drilling fluids. Based on sensors monitoring the surface or bottom hole parameters, detection seems to be the most cost-effective solution, but it lacks accuracy, or in most cases, the response time will increase; the development of a complex bright drill pipe due to its high cost and the attendant potential complexity of the entire drilling process in most cases prohibited their routine use. Machine learning algorithms can process and analyze large amounts of data generated when drilling for oil and gas. These methods seem to produce more accurate results based on the patterns created by the algorithm. However, the reliability of the results is easily questioned because the physical meaning of the output is only sometimes obvious, and the scope of application is usually limited [9].

3. Comprehensive Analysis of Logging Technology Optimizes Sensitive Parameters

Given the influence of lithology, physical properties, and engineering parameters on conventional logging fluid identification, the gas measurement data are not affected by formation lithology, and its advantages are real-time, sensitivity, rapidity, and less influence by human factors. This includes but is not limited to establishing the distribution profile of underground rock strata, determining the stratigraphic position of the actual drilling site, providing geological information such as formation structure and lithology, and providing information about formation fractures and pore structures to help evaluate the development prospects and conditions of horizontal wells, and help to determine the location of highly permeable fracture zones in rocks to guide drilling and development work [10]. However, for strata whose properties cannot be determined by direct observation or measurement, the ability to reflect them is limited, and there are some limitations in stratigraphic correlation. In addition, with the continuous improvement in drilling technology, including the introduction of various new drill bits and acceleration technologies, as well as the deepening of oil and gas exploration and development, the understanding of oil and water in reservoirs is becoming increasingly complex. The increasing complexity of Mesozoic igneous rock reservoirs and the continuous improvement in drilling technology

have challenged the accuracy of gas logging in identifying reservoir fluid properties. All these make it more challenging to discover the thin layer, fracture type, and other hidden hydrocarbon reservoirs in Mesozoic igneous rocks.

Therefore, the weight of engineering parameters in the fluid identification of igneous rock reservoirs in the study area was improved, and multi-parameter analysis was carried out by logging. To comprehensively identify fluid properties, gas logging-derived parameters were introduced, including the value of alkanes released by rock cracking per unit volume C_{adjust} , C_1 abnormal multiple values, and the three-dimensional quantitative fluorescence correlation factor N . Its advantage is that it is not affected by the interference and complex physical properties that make it difficult to accurately identify the logging data due to the confusion of lithology classification and naming of igneous rocks in the study area. It is not affected by the process optimization scheme in the project to reduce the accuracy and accuracy of the interpretation of logging data. Based on the characteristic parameters measured by gas, the values of the characteristic parameters in the reservoir and corresponding background parameters are calculated and analyzed. The characteristic parameters with higher oil and gas sensitivity coefficients are investigated. The oil and gas reservoirs are comprehensively interpreted, and the type and properties of reservoir fluids can be effectively identified. Its calculation formula is in (1).

$$\text{Abnormal multiples of characteristic parameters} = \frac{G_f}{G_b} \quad (1)$$

In the formula, background value (G_b): The non-reservoir layer in the upper part of the abnormal reservoir is taken, and the average value of each gas measurement component without noticeable change is calculated. Reservoir representative values (G_f): In the reservoir, the selection range is $C_1 \sim C_6$, and a group of maximum values of C_1 is selected as the representative data. It is the reservoir representative percentage value ratio to the non-reservoir background percentage value. The percentage of total hydrocarbon methane ($C_1\%$) can quickly identify oil and gas reservoirs; its calculation formula is in (2).

$$C_1\% = \frac{C_1}{(C_1 + C_2 + C_3 + iC_4 + nC_4 + iC_5 + nC_5)}, \quad (2)$$

where: C_1 is the percentage of methane in the total hydrocarbon content volume. In the studied structural area, there is a defining relationship between total hydrocarbon methane and the rate of oil and gas, while the gas reservoir can be identified by quickly identifying this relationship [11].

The factors related to gas measurement and engineering parameters are collected into a simplified formula, the gas data are standardized and corrected, and the alkane value released by rock cracking per unit volume can be obtained by substituting each parameter. Due to the different properties of different fluids and different gas–oil ratios, the properties of igneous reservoir fluids can be more accurately identified. The calculation formula is in (3).

$$C_{\text{adjust}} = \frac{L_1 L_2 \times \text{ROP} \times Q \times C_1}{D^2} \quad (3)$$

where: L_1 is the gas conversion coefficient according to the unit time of the released gas and the constant related to the unit conversion; L_2 is the coefficient of gas release efficiency of alkanes. ROP is the time required to drill, min/m; C_1 is the measured methane value, %; D is the drill diameter, mm.

The C_1 abnormal multiple value is the geometric change multiple relationship between the alkane content in the reservoir and the gas content in the stable interval in the cap layer. The calculation formula is in (4).

$$C_1 \text{ Abnormal multiplier value} = \frac{C_1}{C_{1\text{Backdrop}}} \quad (4)$$

where: C_1 is the measured value of the relative content of alkane by the gas measuring equipment, %; The average relative alkane content of the gas stable interval in the $C_{1\text{Backdrop}}$ cap, %.

Conventional fluorescence logging is greatly affected by the interference of unique mud materials and fluorescent organic additives, and the test results easily ignore the identification of light oil, coal oil, and condensate reservoirs. Many human interference factors can only be limited to qualitative interpretation. In general, oil reservoirs show low fluorescence brightness, strong volatilization, a large oil–gas value ratio, and light oil quality [12], making the fluorescence logging display area small, fuzzy, and difficult to distinguish. For example, conventional quantitative fluorescence logging can effectively identify light oil by emitting a laser band between 240 and 350 nm. Nevertheless, some things could be improved in identifying and analyzing medium and heavy oil. Drilling fluid additives, especially in the pollution of drilling fluid additives, and influential oil and gas identification methods have certain limitations [13]. Compared with conventional fluorescence technology, the advantage of three-dimensional quantitative fluorescence is that the width of the emission spectrum is wide during the process of excited sample emission fluorescence; that is, the fluorescence signal is emitted in different wavelength ranges, rather than only focusing on a specific wavelength point, and the excitation wavelength used has a wide range of excitation wavelengths, rather than only a specific excitation wavelength. It can more effectively meet the display of hydrocarbon components under the excitation of the light source, accurately represent the distribution characteristics of hydrocarbons, and help more effectively identify the type of reservoir fluid [14]. The method uses different wavelengths of light to excite and receive different substances, describes the luminescence characteristics of the fluorescent substances according to the fluorescence intensity, converts the received fluorescence signals into electrical signals, and generates three-dimensional quantitative fluorescence data and maps. In the three-dimensional quantitative fluorescence analysis technology, the fluorescence intensity shows an apparent linear relationship with the concentration of fluorescent substances. When the concentration of fluorescent substances is relatively low, the oil concentration in the sample can be quantitatively evaluated with high precision by measuring the change in the fluorescence peak value of the sample in a crude oil solution and using the constructed crude oil calibration curve [15]. The three-dimensional quantitative fluorescence correlation factor N can be used to measure the degree of fluorescence series corresponding to fluorescent substances in the measured sample and to describe the proportion of oil content in the rock sample, and there is a mathematical correlation with the concentration of oil and gas. The calculation formula is in (5).

$$N = 15 - \frac{4 - \lg C}{0.301} \quad (5)$$

In the formula, N is a non-legal unit of measurement without dimension. C is the oil and gas content concentration, mg/L, the proportion of hydrocarbon content extracted in the unit sample, reflecting the oil and gas content in the unit sample tested.

Based on the derived gas parameters introduced and the improved engineering parameters, it can be seen that the reservoir's physical properties are good when the C_{adjust} level is >1.15 , the corresponding 3D quantitative fluorescence correlation factor $N > 4.2$, the C_1 abnormal multiple values > 2.3 , $C_1\%$ > 0.76 , and the logging data are interpreted as an effective oil reservoir. When the C_{adjust} value is less than 1.15, the reservoir's physical properties are poor, corresponding to the three-dimensional quantitative fluorescence correlation factor $N < 4.2$, and the C_1 abnormal multiple values < 2.3 ; the logging data explain that the oil properties are poor and that it is an invalid oil reservoir. The evaluation indicators are as follows (Table 1).

Table 1. Multi-parameter evaluation index based on gas measurements.

Reservoir Evaluation Categories	C _{adjust}	N	C ₁ %	C ₁ Abnormal Multiple Value
Effective reservoir	>1.15	>4.2	>0.76	>2.3
Dead reservoir	<1.15	<4.2	<0.76	<2.3

4. Interactive Chart to Establish Interpretation Standards and Sensitive Parameters Optimization to Establish Interpretation Standards

4.1. Interactive Charts Establish Standards of Interpretation

Currently, the usual chart method in the gas logging interpretation chart is widely used in identifying fluids, especially oil and gas formations, including the Pickler chart, hydrocarbon triangle chart, and gas ratio method [16]. It is found that the triangular pattern of the light oil layer is usually in the shape of a medium-sized equilateral triangle or an inverted triangle, which indicates the fluid characteristics of the oil-to-gas zone. The Pickler's chart mainly explains hydrocarbon fluids dominated by gas, and some explain hydrocarbon fluids containing a small amount of oil, which is generally a similar phenomenon of multiple interpretations. It is impossible to accurately identify Mesozoic oil and gas formations and the chart cannot clearly show interface characteristics.

Therefore, sensitivity analysis and optimization of characteristic parameters were carried out for data and related logging data reflecting fluid properties in gas measurement and geochemistry. Due to the different depths of test intervals in different test wells and the differences in data records during the test process, there were outliers in the actual test data, or some data were missing, which made it impossible to apply the data directly. Missing value processing and outlier detection must be carried out first to achieve data normalization and obtain better parameters. The missing value processing method deletes the sample group with missing values or fills the sample or feature with missing values. In the study area of this paper, the parameters of porosity and permeability are complete, but other parameters are missing to varying degrees, so the latter method is chosen to deal with the missing value. The group with similar porosity and permeability is selected for the missing values of other parameters, and the mean value of its corresponding characteristics is used to fill it. The detected outliers are removed and populated in the same way. Maximum–minimum normalization is adopted to implement data normalization and map the data with different dimensions and dimension units on a unified scale. This method retains the relationship in the original data and is the simplest method to eliminate the impact of dimension and value range. Its calculation formula is in (6).

$$X^* = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (6)$$

In the formula, X^* is the normalized data, X_i is the original data, $X_{\max}$ is the maximum data value, and $X_{\min}$ is the minimum data value. All values have no dimension.

Correlation analysis of gas data and geochemical data is carried out. The parameters S0 and S1 with high correlation are selected (Figure 3). An evaluation factor was constructed based on factor analysis. An interactive chart was established (Figure 4). An intersection analysis of gas and geochemical logging data was carried out. It was found that geochemical logging parameters S0 and S1 (Table 2) could better distinguish different fluid properties. According to the statistics of geochemical parameters S0, S1, and S2 of different fluid properties (Table 3), it can be seen that the oil layer and oil–water co-layer are higher than the water layer and dry layer. The water and dry layers show shallow values regarding geochemical parameters (Figure 5).

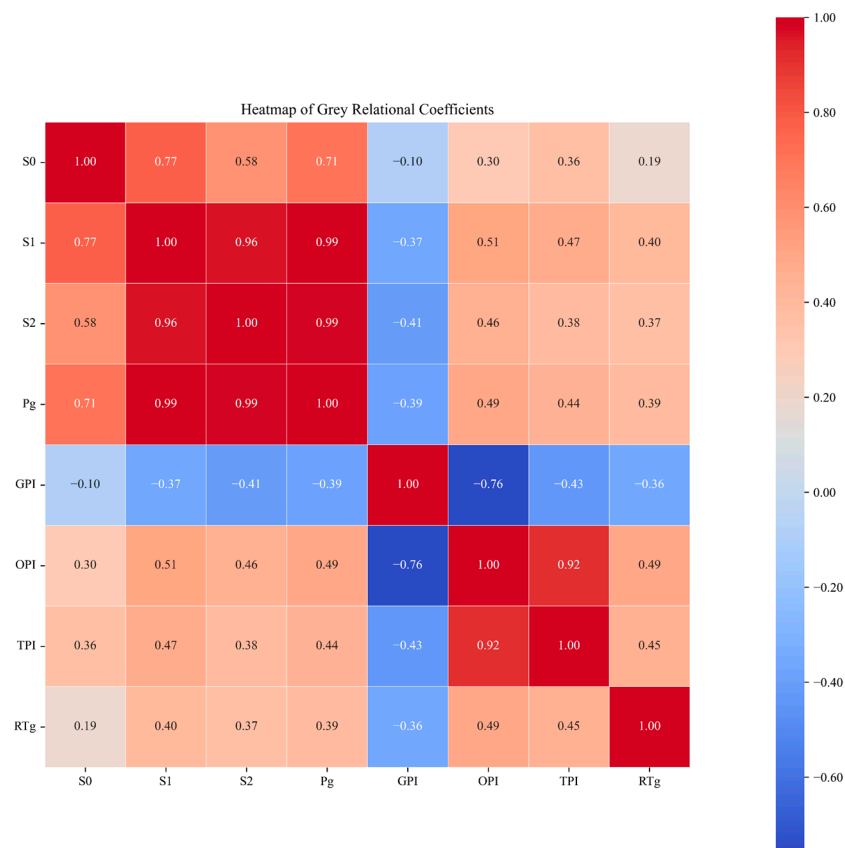


Figure 3. Correlation analysis of preferred parameters.

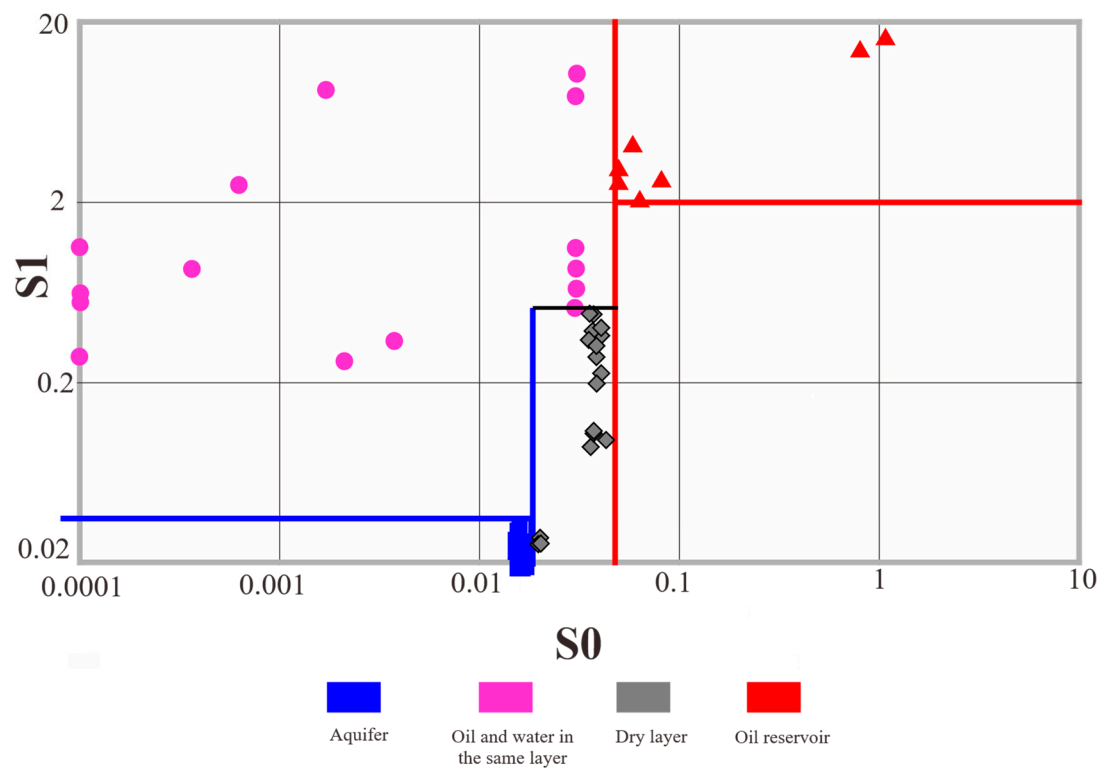


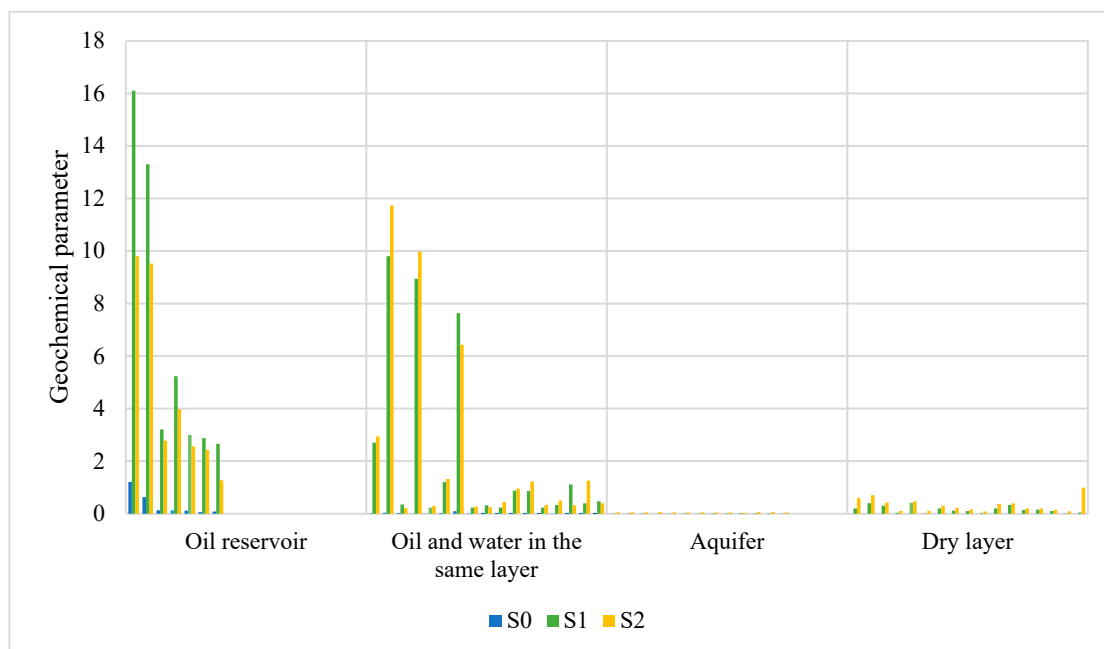
Figure 4. Explanation of interactive graphics for geochemical parameters S1 and S0.

Table 2. Optimal statistical analysis of geochemical parameters.

	Oil Reservoir	Oil and Water in the Same Layer	Aquifer	Dry Layer
S0	>0.04	<0.03	<0.02	$0.02 < S0 < 0.04$
S1	>2	$S0 < 0.02$ $0.02 < S0 < 0.03, S1 > 0.41$	<0.045	<0.41

Table 3. Statistical analysis of geochemical parameters.

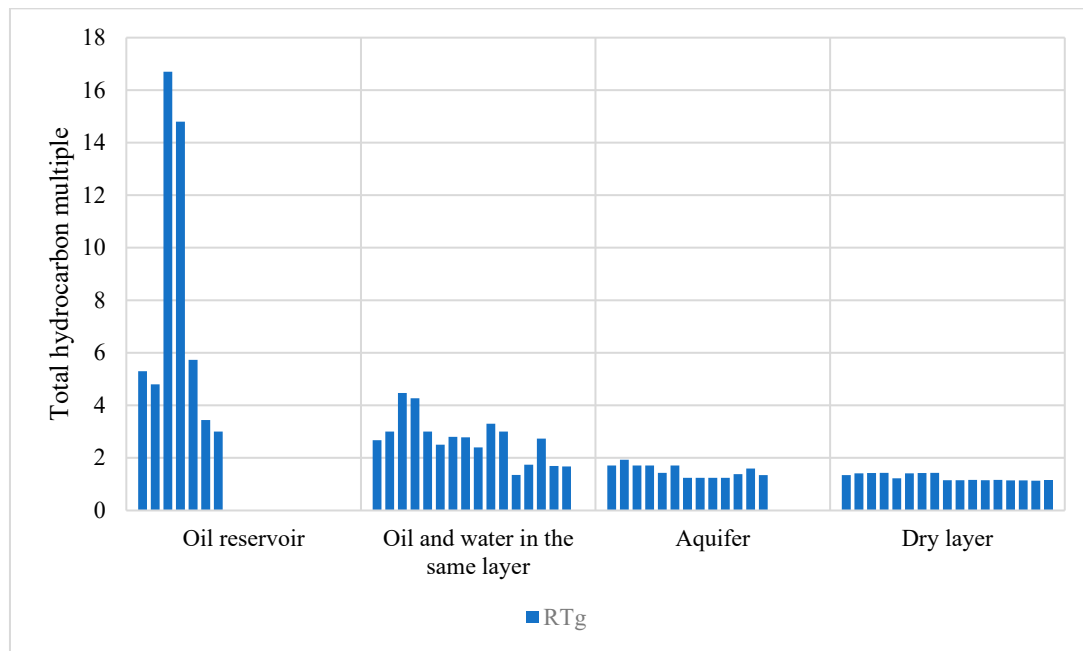
Geochemical Parameter	Oil Reservoir			Oil and Water in the Same Layer			Aquifer			Dry Layer		
	Peak value	Low value	Mean value	Peak value	Low value	Mean value	Peak value	Low value	Mean value	Peak value	Low value	Mean value
S0	1.079	0.044	0.282	0.029	0.0001	0.014	0.018	0.017	0.017	0.039	0.021	0.032
S1	15.874	2.263	6.437	9.616	0.258	2.143	0.043	0.021	0.031	0.401	0.025	0.179
S2	10.116	1.507	4.493	11.514	0.25	2.332	0.164	0.048	0.09	1.295	0.113	0.532

**Figure 5.** Fluid identification of geochemical parameters.

According to the statistics of total hydrocarbon multiples measured by gas for different fluid properties (Table 4), the total hydrocarbon multiples of oil reservoirs are generally high, the oil–water layer is slightly lower than the oil layer, the water layer and the dry layer are basically the same (Figure 6), and the total hydrocarbon values are basically close to the background values measured by gas (that is, the multiples are 1).

Table 4. Statistical analysis of gas measurement parameters.

	Oil Reservoir			Oil and Water in the Same Layer			Aquifer			Dry Layer		
Aerometric parameters	Peak value	Low value	Mean value	Peak value	Low value	Mean value	Peak value	Low value	Mean value	Peak value	Low value	Mean value
Total hydrocarbon multiple	16.3	3	7.32	4.4	1.033	2.353	1.75	1	1.288	1.25	1	1.088

**Figure 6.** Fluid identification based on total hydrocarbon multiple.

4.2. Interactive Criteria Are Preferably Established for Sensitive Parameters

As the current igneous fluid identification methods mainly rely on the evaluation method of logging single parameter construction, they are primarily a qualitative identification due to lithology, physical property, and engineering factors and need more systematic and comprehensive evaluation and analysis of logging data. Conventional igneous rock logging data are affected by the confusion of lithology classification and naming, resulting in the non-obvious response characteristics of conventional logging of reservoir fluid properties in Mesozoic buried hills. The hardness, composition, and density of different lithologies lead to the different permeability and porosity of various igneous rocks, which makes the reservoir physical properties of other types of igneous rocks different, and the composition of the reservoir space very complicated, thereby rendering the reservoir fluid properties more difficult to identify. The influence of engineering parameters also reduces the accuracy of interpretation and data of conventional logging methods and intensifies the interference in accurately identifying oil and gas formations.

Based on correlation analysis, five parameters (S1, GPI, OPI, TPI, and total hydrocarbon multiple RTg) are selected for the gas and geochemical data unaffected above (Table 5). After normalization, a gray correlation degree is used to determine the weight of each parameter. Calibration data such as testing, sampling, analysis, and laboratory testing are used based on parameter sensitivity analysis. The multi-parameter coupling fluid identification quantitative characterization index FI is constructed for logging, and its

calculation formula is in (7) and (8). Combined with the test data, the corresponding fluid evaluation criteria were established (Figure 7), and the fluid type was identified (Table 6).

$$FI = (x + a)^n = \sum_{i=1}^n (w_1 P_1 + w_2 P_2 + \dots w_n P_n) \quad (7)$$

where: $P_1, P_2, \dots, P_n$ is a normalized logging parameter with no dimension. $w_1, w_2, \dots, w_n$ is the weight of each logging parameter, and a is a constant without dimension.

$$FI = w_{GPI} GPI_{norm} - w_{S1} S1_{norm} - w_{OPI} OPI_{norm} - w_{TPI} TPI_{norm} - w_{RTg} RTg_{norm} \quad (8)$$

where: $S1_{norm}, GPI_{norm}, OPI_{norm}, TPI_{norm}, RTg_{norm}$ are the preferred normalized processing parameters with no dimension.

Table 5. Statistical analysis of weight parameter coefficients.

Parameters	$S1_{norm}$	GPI_{norm}	OPI_{norm}	TPI_{norm}	RTg_{norm}
Weight coefficient	0.094	0.027	0.234	0.24	0.204

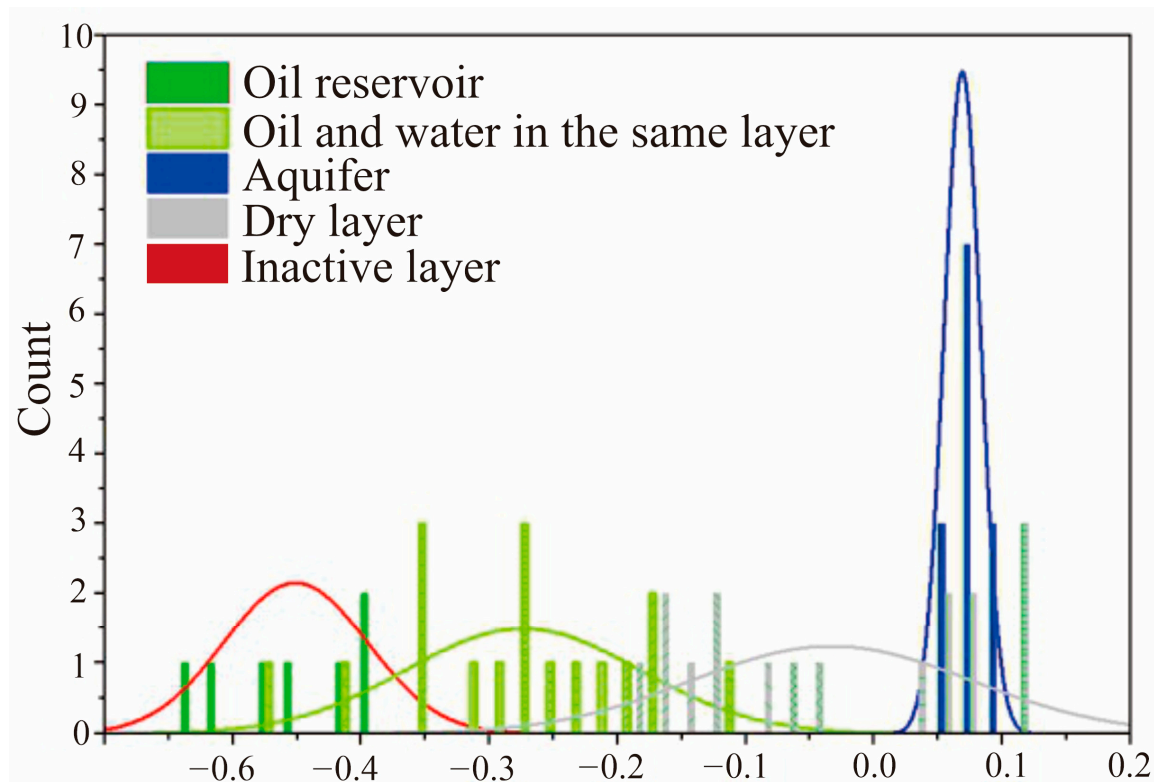


Figure 7. Fluid evaluation indicators.

Table 6. Identifying fluid types based on FI parameters.

	Oil Reservoir	Oil and Water in the Same Layer	Aquifer	Dry Layer
FI	<−0.36	−0.36~−0.15	−0.15~0.04	>0.04

5. Applied Interpretative Analysis

Four wells of the same type, PL9-1-1, PL9-1-4, PL9-1-5, and PL9-1-10, were analyzed based on the established multi-parameter coupling fluid quantitative characterization index FI; the oil layer is less than −0.36; −0.36 to −0.15 is the same layer of oil and water; the

water layer is from -0.15 to 0.04 , and the dry layer is greater than 0.04 . The geochemical logging parameters S_0 and S_1 can distinguish different fluid properties well; when S_0 is more significant than 0.04 and S_1 is greater than 2 , it is an oil reservoir. When S_0 is more significant than 0.02 and less than 0.03 , and S_1 is more significant than 0.41 , it is the same layer of oil and water. S_0 is less than 0.02 , and S_1 is less than 0.045 . The water layer is when S_0 is more significant than 0.02 and less than 0.04 , and S_1 is less than 0.41 . At the same time, combined with the evaluation of gas-derived parameters and improved engineering parameters, the variation in gas measured C_1 is between 0.05% and 1.66% , the C_1 abnormal multiple values are between 1.4 and 4.3 , the three-dimensional quantitative fluorescence correlation factor N is between 2.5 and 5.8 , and the value of alkanes released by rock cracking per unit volume C_{adjust} is between 0.1 and 1.7 . In the $1372\text{--}1417\text{ m}$ interval, the gas data show that the C_1 content reaches 1.6635% , the C_1 abnormal multiple values are 4.3 , the value of alkanes released by rock cracking per unit volume C_{adjust} is 1.747 , and the 3D quantitative fluorescence correlation factor N is 5.8 . These parameters show significantly high values, indicating the potential high oil-bearing characteristics of the reservoir. According to the multi-parameter coupling fluid quantitative characterization index FI , the oil layer is less than -0.36 , comprehensively interpreted as an oil layer. The deep resistivity value of logging is $76.7\text{ ohm}\cdot\text{m}$, the shale content is 7.8% , the effective nuclear magnetic porosity is 15.9% , and the nuclear magnetic permeability is $0.066.3\text{ }\mu\text{m}^2$. This comprehensive parameter analysis shows that the reservoir has good oil storage capacity. In the $1434\text{--}1478\text{ m}$ interval, the gas data show that the C_1 content decreases to 0.0543% , the C_1 abnormal multiple values decrease to 1.4 , the values of alkanes released by rock cracking per unit volume C_{adjust} decreases to 0.102 , the P_g value of geochemical logging cuttings is low, and the 3D quantitative fluorescence correlation factor N is 2.5 . If the value is more significant than 0.04 , it is considered a dry layer, which is determined to be an ineffective oil reservoir and comprehensively interpreted as a dry layer. The measured resistivity of the sounding part is $288.5\text{ ohm}\cdot\text{m}$, the shale content is 8.7% , the effective nuclear magnetic porosity is 8.4% , and the nuclear magnetic permeability is $0.013.2\text{ }\mu\text{m}^2$, which is interpreted as a reservoir with poor oil storage capacity according to the logging data. The comparison of data was the same (Figure 8).

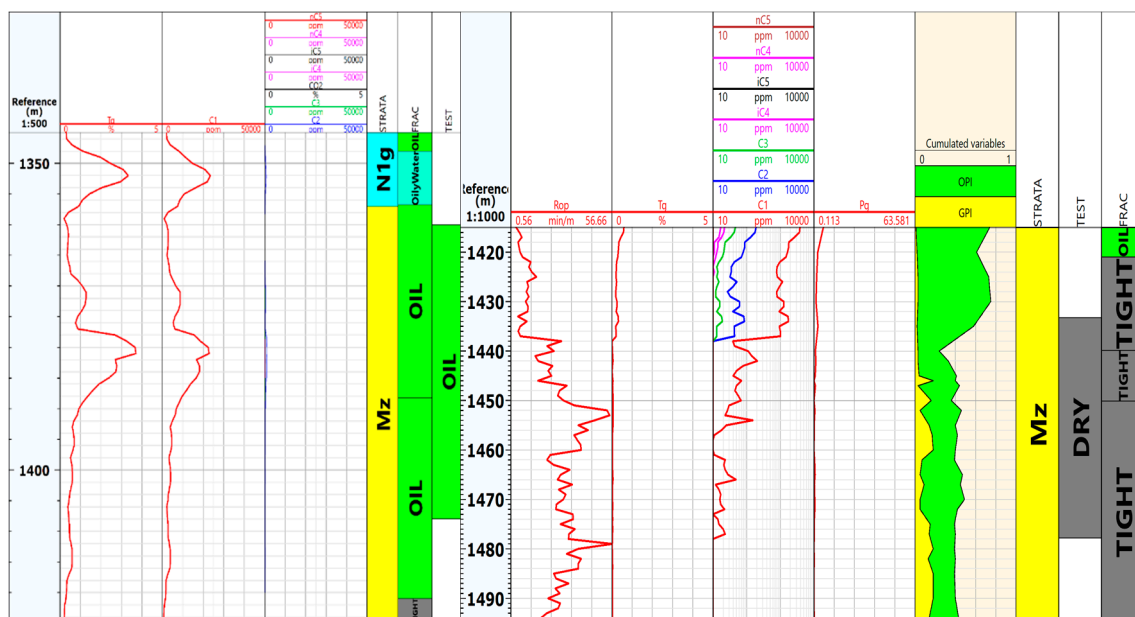


Figure 8. Data comparison. In the figure, the green background is the selected OPI parameter, the yellow background is the selected GPI parameter, the gray background is the dry layer, and the blue is the water layer.

6. Conclusions

(1) By using gas logging-derived parameters and improved engineering parameters, the value of alkanes released by rock cracking per unit volume C_{adjust} , C_1 abnormal multiple values, and three-dimensional quantitative fluorescence correlation factor N of rock cracking released per unit volume were comprehensively considered and judged. To reduce the influence of lithology and physical properties and improve the influence of engineering parameters, multi-parameter establishment evaluation indexes were established. The sensitivity analysis and optimization of characteristic parameters were carried out based on gas and geochemical logging data and related logging data. Evaluation factors were constructed based on factor analysis, and interactive charts were established. Through the cross-analysis of gas survey and geochemical logging data, it can be seen that geochemical logging parameters S_0 and S_1 can distinguish different fluid properties well, and statistical geochemical parameters S_0 , S_1 , and S_2 of different fluid properties show that oil reservoirs and oil–water reservoirs are higher than water reservoirs and dry reservoirs. The water and dry layers show extremely low values regarding geochemical parameters, indicating that the intersection chart can be used for effective reservoir fluid identification.

(2) Through comprehensive analysis of gas logging and geochemical data based on correlation analysis, five parameters of S_1 , GPI, OPI, TPI and total hydrocarbon multiple RTg were selected. After normalization, the weight of each parameter was determined by the gray correlation degree. The quantitative characterization index FI of logging multi-parameter coupling fluid identification was constructed using data calibration for testing, sampling, and analysis based on parameter sensitivity analysis. At the same time, the evaluation criteria were established by combining gas logging derivative parameters and improving engineering parameters to effectively identify the fluid properties of igneous rock reservoirs. The results were verified by comparing the sampling test results of the PL9-1 well area. Combined with the multi-parameter method, the accuracy of analysis and interpretation reaches 80%, which helps to quickly identify the fluid properties of igneous rock reservoirs in the study area and has guiding significance for improving the accurate evaluation of mud logging data and increasing exploration benefits.

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References

1. Zhang, X.Q.; Zhang, J.B.; Yuan, Y.D.; Peng, C. Comprehensive logging evaluation method for the Mesozoic igneous rock hidden mountains in the northern slope of the Bohai South low uplift. *J. Petrochem. Technol.* **2023**, *30*, 150–152.
2. Wang, C.J.; Zhang, X.T.; Xu, C.Q.; Yu, Y.; Guo, Y.Y. Main controlling factors of high-quality reservoirs in the Mesozoic volcanic rocks of the 428 structure in the Bohai Central Depression. *J. Mar. Geol. Front.* **2022**, *38*, 69–75.
3. Chen, G.C.; Chen, H.J.; Tian, X.P. Development characteristics and controlling factors of granite buried hill reservoir in PL oilfield, Bohai Sea. *J. Mar. Geol. Front.* **2016**, *32*, 14–19.
4. Zhang, Z.B.; Guo, M.Y.; Yuan, S.B.; Liu, J.X.; Ji, J.F.; Yang, Y.; Huang, X.G. Drilling-while-logging interpretation and evaluation of fracture-type reservoir in the Mesozoic igneous rock hidden mountains in the western Liaoning uplift. *J. Mar. Geol. Front.* **2021**, *37*, 73–79.
5. Zhang, H.G.; Wang, X.; Lu, F.T.; Guan, D.Y.; Gao, K.S. Study the Mesozoic volcanic rock reservoirs in the central Bohai Bay and target area prediction. *J. J. Southwest Pet. Univ. (Sci. Technol. Ed.)* **2015**, *37*, 47–54.
6. Zhong, W.W.; Lu, S.F.; Zhang, S.G.; Huang, W.B.; Shao, M.L.; Wang, L.W. Petrophysical characteristics and influencing factors of igneous rock reservoirs—A case study of Longshen 1 well in the southern Yingtai sag, Songliao Basin. *J. Acta Sedimentol. Sin.* **2010**, *28*, 563–571.

7. Huang, W.D.; Sui, Z.D.; Chen, X.H.; Huang, G.R.; Wu, Z.; Zhao, Y.Q.; Chen, L. Mechanical-energy-based physical property evaluation technology for igneous reservoirs. *J. Logging Eng.* **2019**, *30*, 79–149.
8. Fu, J.Y.; Luo, H.B.; Chen, N.Z.; Zhang, Z.H.; Zhang, L.M.; Wei, S.L. Comprehensive evaluation technology for drilling-while-logging horizontal wells in igneous reservoirs. *J. Logging Eng.* **2022**, *33*, 35–40.
9. Zachopoulos, F.N.; Kokkinos, N.C. Detection methodologies on oil and gas kick: A systematic review. *J. Int. J. Oil Gas Coal Technol.* **2023**, *33*, 1–19. [[CrossRef](#)]
10. Lu, X.C.; Di, M.L.; Wang, W. Discussion on well control measures in Bohai Oilfield. *J. J. Yangtze Univ. (Nat. Sci. Ed.)* **2017**, *14*, 46–49.
11. Sun, F.H. Application extension of gas logging data. *J. Pet. Geol. Eng.* **2023**, *37*, 46–49.
12. Wang, R.K.; Chen, P.; An, D.L.; Hu, K.; Mo, G.Y. Application of comprehensive evaluation technology for rapid identification of complex reservoir fluids based on gas logging data in the Wenchang X area. *J. Logging Eng.* **2022**, *33*, 46–51.
13. Wang, M.D.; Yao, Z.H.; Xia, Z.J.; Cao, M.F.; Zeng, X.W.; Wang, H. On-site operation and rapid interpretation methods of three-dimensional fluorescence logging technology. *J. Chem. Eng. Equip.* **2021**, *5*, 85–87.
14. Yi, B. Integrated application of multiple logging technologies for rapidly identifying fluid types in the Wenchang X area. *J. Chem. Ind. Manag.* **2022**, *31*, 75–78.
15. Guo, S.S.; Yang, H.J.; Liao, M.L.; Chen, X.J.; Chen, C.Y. Application of three-dimensional quantitative fluorescence logging technology in evaluating gas reservoirs in the Lingshui sag of the Qiongdongnan Basin. *J. Logging Eng.* **2015**, *26*, 5–107.
16. Liu, J.X.; Wang, X.; Wu, H.S.; Hu, Y.; Huang, X.G. Gas identification methods and application for condensate gas and light oil. *J. Spec. Oil Gas Reserv.* **2017**, *24*, 48–53.

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