

Lithological characteristics and logging identification methods of the Chang₇₃ member in Jiyuan area, Ordos Basin

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Abstract: The exploration of shale oil is influenced by the type and spatial distribution of sweet spots in the reservoir. Various types of deep-water fine-grained sedimentary rocks are developed in the Chang₇₃ member of the Ordos Basin. By accurately characterizing the lithology, the distribution patterns and control factors of different lithologies are clarified, which is of great significance for the exploration of sweet spots in shale oil reservoirs in the Chang₇₃ member. Drilling coring is the most accurate method for describing lithology, but the cost of coring is high, and the number of coring wells and sections is limited. The vertical resolution of logging curves is high, which can continuously and in situ reflect the characteristics of formation lithology, thus compensating for the problem of insufficient core wells. Based on the differences in electrical properties, physical properties, and radioactivity of different rock types in logging responses, first, by observing and describing 17 core wells inside the basin, it was identified that the Chang₇₃ member mainly developed fine sandstone, siltstone, muddy siltstone, sandy mudstone, mudstone, and black shale. The logging data values of different rock types were statistically analyzed, and the results showed that the natural gamma and acoustic time difference logging curves had a more obvious response to rock types in different sedimentary facies zones. Secondly, by using the intersection diagram method, different logging classification standards for different rock types were identified. Through comparison and verification with core wells, the conformity rate reached over 80%. Finally, 130 wells in the study area were selected for lithology identification, and the identification results were applied to the plan and profile maps. It was found that the distribution of lithology is significantly controlled by the sedimentary system and sedimentary facies, and the lithology is orderly distributed from the delta front (fine sandstone, siltstone) to semi deep lakes (mudstone) and deep lakes (shale).

Keywords: Ordos Basin; Chang₇₃ member; Lithology; Logging identification; Intersection diagram method.

1. Introduction

Fine-grained sedimentary rocks are defined as clastic sedimentary rocks in which the content of particles with a grain size smaller than 62.5 μ m exceeds 50%, accounting for more than two-thirds of the global sedimentary rocks^[1]. In recent years, unconventional oil and gas have gradually emerged as a significant domain for the global supply of new fossil energy resources. The exploration has shifted from "searching for oil and gas outside the source" to "exploring within the source." Fine-grained sedimentary rocks serve not only as crucial source rocks but also function as reservoirs for unconventional oil and gas^[2]. The Chang₇ Member of the Triassic Yanchang Formation in the Ordos Basin is extensively developed with various types of deep-water fine-grained sedimentary rocks. Among these, mud shale constitutes the principal hydrocarbon source rock of the Mesozoic strata in the Ordos Basin and represents a significant unconventional oil and gas resource. Deep-water gravity flow sandstones form important reservoirs for tight oil^[3]. During the depositional period of the Chang₇₃ in the Ordos Basin, the basement of the lake basin experienced rapid subsidence, leading to a substantial influx of sediments into the lake. This period was characterized by swift vertical facies changes and pronounced heterogeneity. Within the mud shale sequences, sandstone interbeds with high natural gamma values developed, making the lithology identification difficult and lacking effective identification methods. Due to the

limited number of coring wells, it is impossible to comprehensively reflect the lithological characteristics of the study area solely through core observations. However, logging curve data can continuously and in-situ reflect the characteristics of formation lithology^[4]. Therefore, integrating well logging data with core data can effectively compensate for the insufficiency of coring information. Previous studies have primarily employed the well log overlay method and the crossplot method^[4-11]. Huang Wei^[10] utilized the well log overlay method to identify the shale gas reservoirs in the Yanchang Formation of the Ordos Basin. The results indicated that the overlay method can effectively distinguish between sandstone and mudstone, with particularly pronounced efficacy in identifying organic-rich shale. However, the method's performance in recognizing transitional lithologies such as argillaceous siltstone and silty mudstone was less effective. Yan Ziyuan^[5] used the cross-plot method to identify the lithologies in the Chang₇₃ segment of the Ordos Basin. For the Chang₇₃ member where source rocks are developed, the cross-plot method can effectively distinguish between siltstone, fine sandstone, and source rocks, but the differentiation between silty mudstone and muddy siltstone remains less distinct. Cheng Dawei^[4] utilized both the cross-plot method and the well-logging curve calculation method respectively to identify and apply lithologies in the Chang₇ Member of the western-central Ordos Basin. Through comparison, it was concluded that the cross-plot method offers higher accuracy in lithology

identification, exceeding 86%.

In this paper, the cross-plot method with high accuracy is used to identify the lithology. Within the study area, ten cored wells from different sedimentary facies belts were selected, and the corresponding well-logging curve data were plotted on coordinate systems to summarize the logging response characteristics of different lithologies. Based on these characteristics, logging classification criteria were established. Subsequently, the lithologies of 130 wells in the study area were identified according to these logging classification criteria. Through the accurate characterization of lithology, the distribution patterns and controlling factors of different lithologies in both planar and cross-sectional views were clarified, providing support for the prediction of reservoir "sweet spots".

2. Geological Background

The Ordos Basin is located in the western part of the North China Craton. It is a multi-superimposed basin developed on the basis of the Archean Early Proterozoic crystalline basement^[12]. During the Late Triassic, the inland depression basin began to develop. The basin experienced a complete sedimentary cycle from lake transgression to lake regression. A set of fluvial - delta - lacustrine facies clastic rocks with a thickness of about 1000 - 1300 m, namely the Yanchang Formation, was deposited in the basin^[13]. The middle Member 7 of the Yanchang Formation was deposited during the maximum lake flooding period, with a set of fine-grained clastic rocks about 80-120m thick^[14]. Among them, the black mudstones and shales of the Chang7₃ member are the most important source rocks for the Mesozoic petroleum system^[15]. In addition to mudstones and shales, a large amount of fine-grained materials in the semi - deep to deep lake areas and their peripheral regions can serve as good reservoirs.

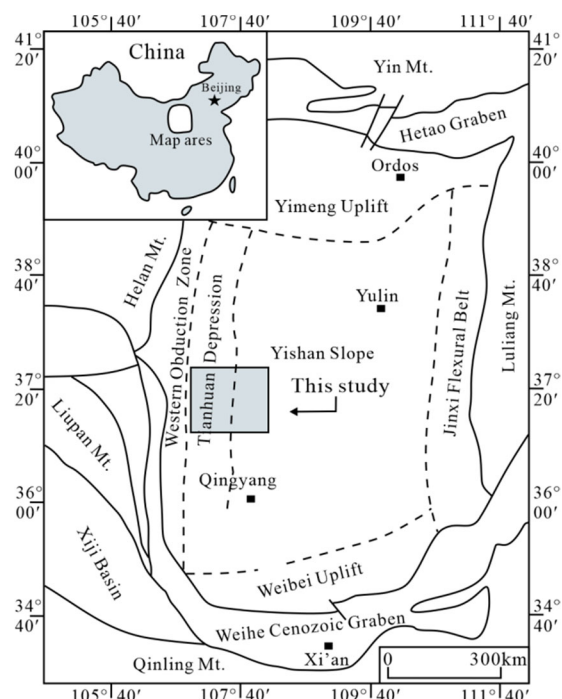


Figure 1. Structural zoning and study area location in the Ordos Basin

3. Rock Type and Characteristics

Based on the observation and analysis of over 600 meters of core samples from 17 wells within the study area and

adjacent regions, combined with outcrop investigations in the basin, six predominant lithological types have been identified in the Chang7₃ member: black shale, mudstone, argillaceous siltstone, silty mudstone, siltstone, and fine-grained sandstone.

3.1. Characteristics of black shale

Black shale is predominantly developed within deep to semi-deep lacustrine subfacies, characterized by clastic particles with diameters less than 4 μ m. In core samples, it typically appears brownish-black to black, exhibits well-developed lamination, and commonly contains ichthyolith fossils. These shales are distinguished by significant thickness and moderate thermal maturity, serving as high-quality hydrocarbon source rocks within the Mesozoic strata of the Ordos Basin^[3]. In outcrop exposures, black shale displays a grayish-black hue with pronounced lamination, demonstrating high susceptibility to weathering-induced fragmentation. Tuffaceous interbeds (grayish-yellow in color) are frequently observed within the shale sequences. Logging responses of black shale include: High natural gamma (180-330 API) and acoustic moveout values (280-340 μ s/m), Low density (2.2-2.4 g/cm³), Negative spontaneous potential anomalies (Table 1).

3.2. Characteristics of mudstone

Mudstone is predominantly developed in sedimentary facies such as deep to semi-deep lacustrine environments and delta-front interdistributary bays, characterized by clastic particles with diameters below 4 μ m. It typically exhibits colors ranging from grayish-black, black, to dark gray, displaying a massive structure with poorly developed lamination. The rock is organic-rich and commonly contains plant fossils. The distinction between mudstone and shale primarily lies in the degree of lamination development. Logging responses of mudstone include: Moderate to high natural gamma values (130-160 API), Elevated acoustic moveout values (260-300 μ s/m), Low density (2.4-2.5 g/cm³), Near-baseline spontaneous potential (Table 1).

3.3. Characteristics of silty mudstone

Silty mudstone predominantly exhibits dark gray to grayish-black coloration, with clastic particle diameters ranging between 4-10 μ m. In core samples, it typically displays normal grading, transitioning upward from silty mudstone at the base to pure mudstone at the top. The basal silty mudstone commonly contains horizontal laminations, corresponding to the D-E divisions of the Bouma sequence in turbidite deposits. Logging responses of silty mudstone include: Moderate natural gamma values (100-130 API), Low acoustic moveout (210-230 μ s/m), High density (2.6-2.66 g/cm³), Near-baseline spontaneous potential (Table 1).

3.4. Characteristics of Argillaceous siltstone

Argillaceous siltstone predominantly exhibits dark gray to gray coloration, with clastic particle diameters ranging from 4-10 μ m. In core observations, it is characterized by thin interbeds of siltstone and mudstone, primarily deposited in delta-front interdistributary bays and as Bouma Sequence divisions D-E in turbidite systems. Delta-front deposits typically display sharp contacts between sand and mud layers with moderate sorting, whereas turbidite deposits show gradual transitional contacts between silty and muddy intervals. The rock commonly contains sedimentary structures such as deformation structures, horizontal bedding,

and rhythmic bedding. Logging responses include: Moderate natural gamma values (90-115 API), Low acoustic moveout (210-240 $\mu\text{s}/\text{m}$), High density (2.55-2.65 g/cm^3), Near-baseline spontaneous potential (Table 1).

3.5. Characteristics of siltstone

Siltstone predominantly exhibits dark gray to gray coloration and is commonly associated with depositional environments such as delta-front interdistributary bays, small-scale sandy debris flows, and turbidite deposits. Clastic particles within siltstone have diameters exceeding $10\mu\text{m}$. It typically occurs as thin beds intercalated with mudstone in near-horizontal alternations, characterized by gradational contacts between sandy and muddy layers. Sedimentary structures include horizontal bedding, wavy bedding, and graded bedding. Locally within the basin, siltstone layers undergo sliding deformation, forming small-scale sandy debris flows that erode underlying mudstone or thin mudstone interbeds within siltstone sequences. These processes generate mud clasts through fragmentation and subsequent transport. Logging responses of siltstone include: Low natural gamma values (85-110 API), Low acoustic moveout (205-245

$\mu\text{s}/\text{m}$), High density (2.5–2.65 g/cm^3), Negative spontaneous potential anomalies (Table 1).

3.6. Characteristics of fine-grained sandstone

Fine-grained sandstone predominantly exhibits gray, grayish-white, and grayish-green coloration, with clastic particles exceeding $10\mu\text{m}$ in diameter. It is primarily associated with delta-front subaqueous distributary channels and sandy debris flow deposits. Sedimentary structures vary significantly based on genetic mechanisms: Delta-front subaqueous distributary channel sandbodies: Dominated by cross-bedding under tractive current processes. Slump/slide-derived sandstones: Characterized by abrupt sand-mud contacts, slip planes, and convolute bedding. Slump transport phases exhibit high kinetic energy and erosional capacity, frequently incorporating eroded and entrained mud clasts. Sandy debris flow-originated fine-grained sandstone: Typically displays massive bedding, with mudstone rip-up clasts embedded within structureless sandstone units. Logging responses include: Low natural gamma values (50-90 API), Low acoustic moveout (190-220 $\mu\text{s}/\text{m}$), High density (2.5-2.7 g/cm^3), Negative spontaneous potential anomalies (Table 1).

Table 1. Lithological types and logging characteristics of the Chang7₃ member of the in the Ordos Basin

lithology	shale	mudstone	argillaceous siltstone	silty mudstone	siltstone	fine sandstone
granularity/ μm	<4	<4	4–10	4–10	>10	>10
SP/mV	Negative anomaly	Close to baseline	Close to baseline	Close to baseline	negative anomaly	negative anomaly
GR/API	180~330	130~160	100~130	90~115	85~110	50~90
AC/($\mu\text{s}/\text{m}$)	280~340	260~300	210~230	210~240	205~245	190~220
DEN/(g/cm^3)	2.2~2.4	2.4~2.5	2.6~2.66	2.55~2.65	2.5~2.65	2.5~2.7

Logging curve shape

4. Rock Logging Characteristics and Identification Methods

4.1. Characterization of Lithological Logging Responses in Cored Intervals

By observing and describing the lithological characteristics of 10 core wells in the study area, including 5 wells located in the deep lake semi deep lake subfacies and 5 wells located in the delta front subfacies, four logging curves including natural gamma (GR), acoustic moveout (AC), neutron porosity (CNL), and density (DEN) were selected, and 1821 logging data points were analyzed.

The statistical results (Table 2, Table 3) indicate that there are significant differences in the logging characteristics of different sedimentary facies zones, and the response of acoustic time difference and natural gamma logging curves to

lithology is more obvious. In the case of the same lithology, the natural gamma value of the delta front subfacies in the Chang7₃ member is significantly lower than that in the deep lake semi deep lake area. The highest natural gamma value of shale in the delta front area can reach 240.7 API, with an average of 163.4 API, while the natural gamma value of shale in the deep lake semi deep lake subfacies can reach 422.9 API, with an average of 241.3 API. The natural gamma value of the deep lake semi deep lake subfacies is generally higher. Under the same lithology, acoustic moveout in the delta front is slightly higher than that in the deep lake semi deep lake area. The neutron porosity and density logging values of the same lithology show little difference in the delta front and deep lake semi deep lake sub zones, and the pattern is not obvious. The variation of logging values for different rock types is clearly controlled by sedimentary facies zones, which control the distribution range of logging values for different rock types.

In addition, the changes in lithology generally range from fine sandstone, siltstone, argillaceous siltstone, silty mudstone, mudstone to shale. The values of natural gamma, acoustic moveout, and neutron porosity show an increasing trend,

while the density value decreases slightly, especially for shale, where the density value is significantly lower than other rock types.

Table 2. Logging values of different lithologies in the subfacies of the delta front

lithology	AC/($\mu\text{s/m}$)	CNL/%	GR/API	DEN/(g/cm^3)
shale	384.1~236.6	88.8~20.3	240.7~112.8	2.5~1.6
	319.3	39.4	163.4	2.3
mudstone	350.4~219.1	49.7~19.1	201.6~91.0	2.7~2.3
	296.6	36.3	132.1	2.5
argillaceous siltstone	245~222.4	27.6~18.9	117.2~87.3	2.7~2.5
	233.5	23.5	102.1	2.6
silty mudstone	259.5~213.6	37.4~15.3	124.9~79.1	2.7~2.5
	228.4	21.1	96.6	2.6
siltstone	235.1~205.4	28.6~11.2	103.8~67.9	2.7~2.5
	225.1	20.2	85.3	2.6
fine sandstone	244.4~190.8	25.6~8.5	96.3~49.5	2.7~2.4
	218.9	17.4	69.4	2.6

Table 3. Logging values of different lithology in the subfacies of deep lake and semi deep lake

lithology	AC/($\mu\text{s/m}$)	CNL/%	GR/API	DEN/(g/cm^3)
shale	366.8~268.1	79.6~25.2	422.9~137.4	2.5~1.9
	314.6	41.7	241.3	2.3
mudstone	321.3~246.7	45.7~20.6	247.2~110.9	2.6~2.4
	288.5	36.4	160.1	2.5
argillaceous siltstone	245.9~210.0	28.7~16.7	140.1~88.9	2.7~2.4
	222.5	19.5	117.2	2.6
silty mudstone	237.9~205.2	27.6~16.4	123.6~84.1	2.7~2.4
	219.4	21.2	102.2	2.6
siltstone	222.6~203.5	25.3~13.7	121.4~72.0	2.7~2.5
	215.8	20.5	98.5	2.6
fine sandstone	230.3~188.3	26.8~12.9	121.8~55.5	2.7~2.5
	207.2	18.2	85.3	2.6

Note: The meaning of fractions in the table $\frac{\text{max} \sim \text{min}}{\text{average}}$

Based on previous research^[16-19], this article believes that there are four main reasons for the differences in logging values of different sedimentary facies lithology: firstly, the clay particles that make up the mud have a larger specific surface area, which can adsorb more ions of radioactive elements during the sedimentation process. In deep lake semi deep lake areas, the sedimentation time of mud particles is longer, the sedimentation rate is slower, and there is sufficient time for ion exchange with radioactive elements. Therefore, the higher the mud content of rocks, the greater the natural gamma value. Moreover, during the Chang7₃ sedimentary period, the lake basin experienced a relatively rapid subsidence, which was more conducive to the formation of a deeper water reducing environment, resulting in a higher organic matter content. Organic matter is prone to adsorb radioactive substances containing uranium and thorium, and the natural gamma value increases with the increase of organic matter content. Secondly, the pore fluid is a low-speed medium relative to the rock skeleton. In the case of the same lithology and unchanged pore fluid, the larger the rock porosity, the smaller the rock sound velocity, and the greater the time difference. The sedimentary facies zone is the innate condition that controls the development of the entire pore, determining the structural and compositional maturity of the reservoir^[20-21]. The hydrodynamic force in the delta front area

is stronger than that in the deep lake semi deep lake area, with good sorting roundness, high maturity, and low mud content, resulting in larger porosity of the same lithology and thus larger acoustic moveout values. Thirdly, shale has a high content of organic matter, which leaves more storage space for free gas after shrinking. The adsorbed gas volume is also larger than other rock types, and the gas content is positively correlated with the acoustic moveout value. Therefore, shale has a higher acoustic moveout value compared to sandstone.

4.2. Identification of lithology logging

Based on the differences in logging curves of different rock types, the intersection chart method is used to perform intersection analysis on different logging curves, which can identify the logging characteristics of different types of rock types and effectively distinguish them. Previous studies^[4] have shown that the natural gamma, acoustic moveout, and neutron porosity in the Jiyuan area are more sensitive to different rock types. Therefore, this article selects natural gamma to conduct intersection analysis with neutron porosity and acoustic moveout. From the intersection plots (Figure 2, Figure 3), it can be seen that the intersection plot method can effectively distinguish between shale and sandstone. The natural gamma value of delta front subfacies shale is generally greater than 100API, the acoustic moveout value is

greater than 260 $\mu\text{s}/\text{m}$, and the neutron porosity value is greater than 25%. The natural gamma value of the deep lake semi deep lake subfacies is greater than 160API, the acoustic moveout value is greater than 260 $\mu\text{s}/\text{m}$, and the neutron porosity value is greater than 30%. The natural gamma value distinction between mudstone and shale is quite obvious. The natural gamma boundary between mudstone and shale in the delta front subfacies is approximately 160API, while the natural gamma boundary between mudstone and shale in the

deep lake semi deep lake subfacies is approximately 200API. The distinction between sandstone types is not clear, and there is a phenomenon of overlap between different rock types. This may be due to the rapid sedimentary phase transition and mixed accumulation of sand and mud during the Chang7₃ sedimentary period in the lake basin, as well as weak vertical mechanical sedimentary differentiation, resulting in smaller differences in logging response between different rock types.

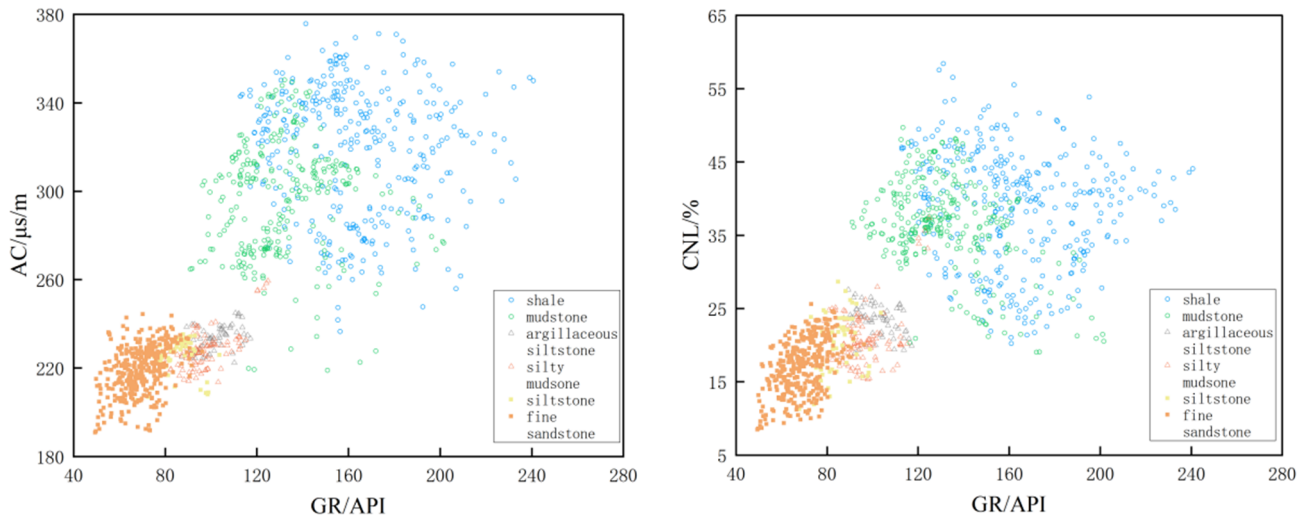


Figure 2. Intersection diagram of different lithology logging in the subfacies of the delta front

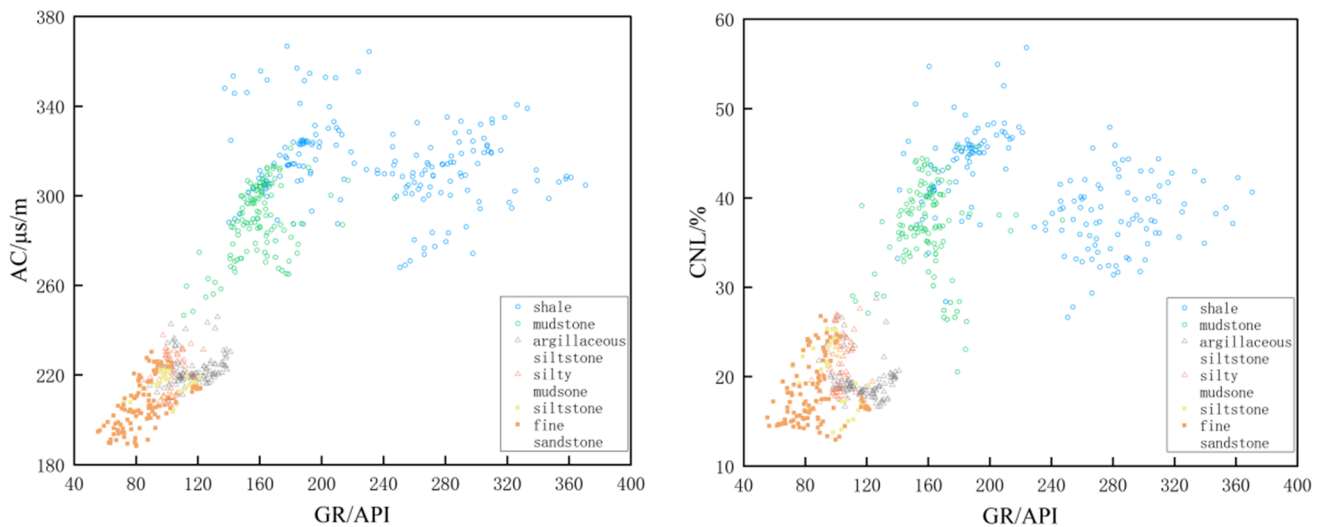


Figure 3. Intersection diagram of different lithology logging in deep lake and semi deep lake subfacies

Regarding the issue of low discrimination between sandstones mentioned above, You^[14] identified high natural gamma sandstones in the Chang7 section of the Ordos Basin by plotting the intersection of deep induction conductivity logging and eight lateral conductivity logging curves. They found that the values between deep induction conductivity logging and eight lateral conductivity logging decreased overall from fine sandstone to mudstone sandstone. In order to expand the logging differences between different lithologies, they multiplied and divided the five logging parameters of acoustic moveout, neutron porosity, natural gamma, deep induction conductivity logging, and eight lateral conductivity logging to acquire two new parameters: $A=(AC-180)*CNL/100$, $B=LN[(CLL8/CLLD)]*DEN$. They plotted

the intersection of the two parameters to reduce the overlapping range of various lithologies and ultimately distinguish them. However, this method has a low degree of differentiation between mudstone and shale. This article believes that using density values of 2.4g/cm³, delta front natural gamma values of 160API, and deep lake semi deep lake natural gamma values of 200API as boundaries can effectively distinguish between mudstone and shale based on the intersection plot and data statistics mentioned above. By comprehensively applying the above methods, one fully coring wells located in the study area were verified, and the conformity rates of W56 well reached 82% , respectively. Practice has proven that this method has a high accuracy rate.

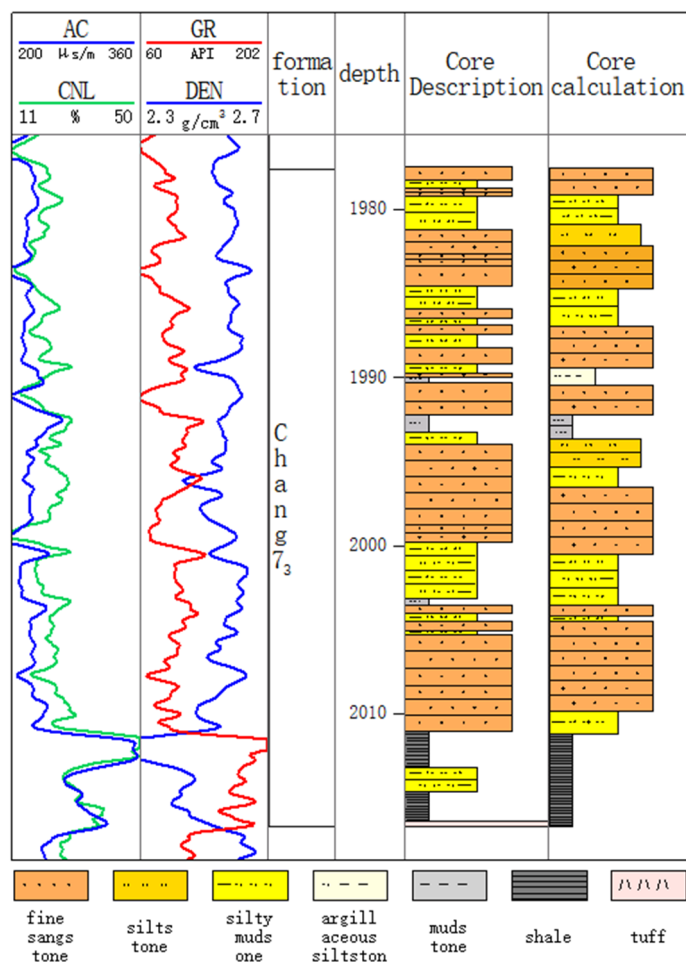


Figure 4. W56 well Comparison between Rock Description and Rock Calculation

5. Conclusion

(1) Through observation of core samples and field outcrops, six main rock types were identified. In different sedimentary facies zones, the response of lithology to acoustic moveout and natural gamma logging curves was most obvious. The changes in the characteristics of lithological logging values generally range from fine sandstone, siltstone, argillaceous sandstone, silty mudstone, mudstone to shale. The values of acoustic moveout, natural gamma, and neutron porosity show an increasing trend, while the density values decrease slightly, especially for shale, where the density values are significantly lower than other lithologies.

(2) By using the intersection chart method, different logging curves are intersected and analyzed, and new parameters are introduced to maximize the differentiation of different rock types. This can effectively distinguish different rock types, compensate for the problem of insufficient coring data, and provide support for understanding the distribution pattern of rock types in the study area.

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