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The application of well logging technology in stratigraphic deposition

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Abstract

Well logging data can be used to determine lithology and for stratigraphic division and correlation. Well logging technology primarily utilizes the geological and physical properties of rock formations, such as electrical conductivity, electrochemical properties, acoustic properties, and radioactivity, to measure their parameters. Spontaneous potential logging utilizes changes in the spontaneous potential curve to classify lithology; natural gamma logging employs gamma curves for lithology classification and stratigraphic correlation to determine shale content; density logging can accurately calculate porosity and distinguish the nature of various fluids in the reservoir; and acoustic logging can be used to delineate the boundary between sandstone and mudstone and to identify gas zones. Essentially, various well logging methods can only indirectly and conditionally reflect certain aspects of the geological characteristics of rock formations. To accurately and comprehensively understand the subsurface geological features and to discover and evaluate hydrocarbon reservoirs, it is necessary to combine multiple well logging methods and pay attention to drilling, mud logging, and other data. Utilizing well logging curve data not only allows for accurate stratigraphic lithology classification but also more vividly represents the depositional environment. By analyzing the shape of the well logging curves and various logging values, it is possible to determine the geometric morphology, lithology, lithofacies, sedimentary structures, ancient water flow and transport directions, and geochemical characteristics of the depositional facies.

Keywords

Well logging technology; Interpretation of well logging data; Characteristics of well logging curves; Sedimentary facies

1.Introduction

Since Schlumberger invented logging technology in 1927 and China applied it to the petroleum industry in 1939, logging technology has developed rapidly. The performance of surface recording systems has significantly improved, and various downhole instruments have enhanced imaging capabilities. Data interpretation is more closely aligned with practical applications in oilfield exploration and development. It is a specialized multi-well logging evaluation technology that primarily relies on logging data and oilfield research data, which are closely integrated [1].

In basic geological research, logging geology can help establish a complete regional stratigraphic sequence framework and further determine its depositional system. In addition, guided by structural geology, logging technology is widely used in the compilation of structural maps, determination of the nature, attitude, developmental patterns, and distribution of structural fractures. In petroleum geological research, using logging technology to identify oil, water, and gas layers, as well as to determine reservoir porosity, are conventional methods for addressing petroleum geological issues. Judging source-reservoir-cap rock combinations based on different logging responses is also one of the practical problems it solves.

Logging data contains abundant geological information, including a wealth of sedimentological information. With the improvement of logging data interpretation methods and the continuous renewal and development of logging technology, especially the application of new-generation imaging logging technology, the sedimentological information obtained from logging data has become increasingly rich, greatly supplementing the shortcomings of drill core sampling. The increase in various logging data analysis methods has also invigorated sedimentological research based on logging data.

Using logging curve data can not only accurately classify stratigraphic lithology but also more vividly represent depositional environments. Therefore, curve morphological characteristics are also important indicators of depositional environments. If the morphological characteristics of logging curves are understood in advance, these characteristics can be used to make more reasonable geological interpretations, thereby providing more valuable geological references for analyzing depositional environments. By analyzing the logging curve characteristics of multiple completed drilling holes in the study area and summarizing the response values of the curves on different lithologies, we seek the relationship between them and genetic indicators, mainly analyzing changes in mud content, bedding, grain size, sorting, and other genetic indicators. Combining drill core data with curve morphology comparisons, we discover the intrinsic connection between different curve morphologies and the depositional environments at that time.

The research content of logging sedimentology mainly includes sedimentary structure analysis, interpretation of depositional environments and paleogeography, geochemical analysis, and ancient water flow directions. These studies can combine the geological application of logging data with oil and gas development, conducting oil and gas research from a three-dimensional perspective, with the analysis of facies and depositional environments being particularly important. With the development of technology and theory, facies have also evolved into various types such as depositional facies and logging facies. This article mainly introduces logging technology and its application in depositional facies. Logging technology plays a significant role in aspects such as lithology, lithofacies, sedimentary structures, geometric morphology of facies bodies, ancient water flow directions, and geochemical analysis.

2. Logging method

Well logging refers to the analysis of the physical properties of different rock formations within a drill hole to determine the geological profile, thereby addressing all underground geological issues, and providing a clear technical overview of the drill hole. This is a geophysical exploration technique first used in the field of coal exploration. China introduced electrical well logging in the early 1950s, and subsequently, various countries and regions around the world have developed numerous different well logging techniques based on the physical characteristics of rock formations [2].

2.1.Logging steps

Well logging first requires drilling operations, where a logging cable is used to lower tools into the drill hole. Subsequently, relevant data is collected and transmitted back to the surface, and various geological parameters obtained by the logging equipment are recorded to form a logging curve. Afterwards, personnel can use the obtained logging curves and geological data to identify underground rock formations and aquifers, and to search for underground coal resources. Currently, the logging techniques in use mainly include resistivity methods, spontaneous potential methods, acoustic methods, gamma logging methods, etc. These logging methods can all effectively meet the measurement requirements for various parameters in coal mine geological exploration.

The specific logical steps are as follows: (1) Observing drill cores and outcrops: Obtain firsthand information on strata, lithology, and structure by observing drill cores and outcrops, and establish models for source-reservoir-cap and sedimentary facies; (2) Geological calibration of well logging: Establish forward and inverse models by calibrating and scaling the well logging curves to determine the relationship between rock properties and electrical properties; (3) Processing well logging data: Evaluate and process basic data, and correct the well logging curves with reference to geological data and well logging information; (4) Geological interpretation of well logging data: Complete the geological interpretation of well logging based on petrophysical research, with reference to existing geological models and the processed results of well logging data.

For geophysical logging, it primarily involves the development of logging instruments based on physical principles. The logging cable is lowered into the target well to ensure that the surface-mounted electrical logging instrument can continuously record parameters along the wellbore as they change with depth. By using curves that represent these parameters, various rock formations distributed underground can be identified, including oil and gas layers, coal seams, and metal ore layers.

For exploration logging, in the context of the petroleum industry, it refers to logging carried out during the exploration process to find new oil fields. It includes: determining underground structures and sedimentary structures through dip logging; identifying lithology and determining the specific locations of oil and gas layers and water-bearing layers through saturation logging; and testing oil and gas layers and water-bearing layers through wireline formation testing.

For development logging, it refers to logging conducted during the extraction process. It can measure the physical properties of rocks in different layers underground and monitor the actual working status of different oil layers in real time. It also inspects the technical condition of the development well, providing a reliable reference for determining and adjusting the operation methods of the development well. Its content mainly includes engineering logging, saturation logging, and production logging.

For acoustic variable density logging, since the propagation speed, frequency, and amplitude of acoustic waves vary in different media, acoustic logging essentially utilizes this characteristic to analyze the geological profile of the drill hole, thereby judging the quality of the cementing.

2.2. Common logging techniques

Well logging technology primarily utilizes the geological and physical properties of rock formations, such as conductivity, electrochemical properties, acoustic characteristics, and radioactivity, to measure their parameters. It is an interdisciplinary field that measures geophysical parameters of the geological profile around a drill hole, combining knowledge from various disciplines such as electromagnetism, acoustics, nuclear physics, thermodynamics, and mechanics. Different measurement methods correspond to different measurement parameters, which are then used to infer information about underground rock formations. Well logging technology involves physical principles such as electricity, gravity, and seismology, and various instruments and equipment for measuring geophysical parameters are developed based on these principles to carry out various well logging tasks. Well logging technology is an important discipline within geophysical exploration, and with continuous improvements and advancements, it is increasingly being applied to tasks such as stratigraphic division, porosity and permeability calculations, and other petrophysical analyses of rock formations, as well as reservoir prediction, which cannot be solved by surface geophysical exploration [3-4].

2.2.1.Natural potential logging

During the measurement process with downhole instruments, the surface instruments will record a logging curve in real time, known as the spontaneous potential (SP) curve. Spontaneous potential arises from the adsorption-diffusion effects of ions in the rock and is closely related to the composition, structure, and cement content of the rock. Therefore, changes in this curve can be used to determine lithology [5].

Spontaneous potential logging is primarily applied to sand-shale profiles. The shape of the SP curve is generally simple, with easy layer differentiation and distinct geological characteristics, making it useful for calculating the thickness of sand and shale layers. It is relatively easy to distinguish between sand and shale layers. Generally, as the clay content increases and the rock grain size decreases, the amplitude of the spontaneous potential decreases. Therefore, spontaneous potential logging can be used to roughly distinguish between sandstone, mudstone, and shaly sandstone. It should be noted that spontaneous potential logging is only suitable for sand-shale profiles with high-salinity formation water. If the formation water has low salinity or if it is a carbonate rock profile, spontaneous potential logging is not applicable. Spontaneous potential logging can be used for the following purposes: ① determining lithology and delineating permeable layers; ② stratigraphic correlation; ③ calculating formation water resistivity; ④ estimating formation clay content; ⑤ identifying water-flooded zones; ⑥ studying sedimentary facies.

2.2.2.Natural gamma logging

Rocks inherently possess varying degrees of natural radioactivity, and natural gamma logging is a well logging method that measures this natural radioactivity in rocks to study the properties of formations along the wellbore profile based on the amount of natural radioactivity contained within the rocks. In natural gamma logging, a detector converts natural gamma rays into pulse signals, which are then transformed by surface equipment into corresponding potential differences based on the pulse frequency per minute for recording, thereby obtaining a natural gamma ray intensity curve, abbreviated as GR.

Similar to the spontaneous potential curve, the natural gamma ray curve can also be used to distinguish lithology. In terms of assessing the level of natural radioactivity in rocks, among igneous rocks, acidic rocks exhibit stronger radioactivity than basic and ultrabasic rocks. In sedimentary rocks, the natural radioactivity of the rock generally correlates positively with its clay content. Generally speaking, the radioactivity of the three major rock types can be ranked as: igneous rocks > metamorphic rocks > sedimentary rocks. In sand-shale sections, the intensity of natural gamma rays is directly proportional to the clay content of the rock, whereas in carbonate formations, the intensity follows the order of mud shale > argillaceous limestone and argillaceous dolomite > pure dolomite and pure limestone, also correlating with clay content. Additionally, natural gamma rays are widely applied in stratigraphic correlation because they are largely unaffected by interfering factors such as porosity, formation water, and drilling fluids, and are often used to identify paleo-weathering crusts and thin shale layers. Coal seams exhibit very weak radioactivity, but the intensity of natural gamma rays increases with an increase in ash content.

2.2.3.Resistivity logging

The resistivity logging method is also one of the earliest electrical logging techniques, commonly used to study the properties of formations along the wellbore profile by measuring the resistivity values of the formations. Depending on the arrangement of the electrode system during measurement, resistivity logging can be subdivided into two methods: potential electrode system logging and gradient electrode system logging. Generally speaking, the resistivity of rocks cannot be directly measured. Therefore, when conducting resistivity logging, a certain amount of current needs to be injected into the ground, and the resistivity of the rocks is indirectly obtained by analyzing the relationship between the electric field and resistivity.
In practical applications, the gradient potential electrode system is mostly used, and its application scope can be summarized as follows: ① Distinguishing lithology and determining formation boundaries; different formations correspond to different apparent resistivity values, with coal seams typically having the highest apparent resistivity, mudstones the lowest, and sandstone layers falling in between. ② Approximately estimating formation resistivity; ③ Roughly determining the stratification of oil, gas, and water; ④ Formation correlation and geological mapping.

2.2.4.Density logging

Density logging belongs to porosity logging, which measures the gamma ray intensity emitted by various gamma sources and received by the detector after scattering and absorption by the rock formation. During density logging, the gamma rays emitted by the downhole gamma source are absorbed due to scattering, resulting in a decrease in intensity. Finally, the unabsorbed gamma rays are received by the detection probe. The electron density of the rock formation is directly proportional to the amount of gamma scattering and absorption, and inversely proportional to the unabsorbed scattered gamma rays. Therefore, the density curve can basically determine the lithology of different rock formations, and based on this, the porosity can be calculated to distinguish the fluid properties of the reservoir.

2.2.5.Acoustic logging

Acoustic waves propagating in different media exhibit distinct acoustic characteristics, such as significant differences in velocity, amplitude, and frequency. Acoustic logging is a logging method that utilizes the acoustic properties of sound waves in different rocks to study various stratigraphic profiles. Currently, the main methods of acoustic logging include velocity logging, acoustic variable density logging, amplitude logging, and noise logging. The essence of these logging methods is to study lithology by distinguishing the acoustic characteristics in different rocks and to solve related geological problems by utilizing the differences in sound wave propagation velocities in different media. Table 1 below shows the P-wave velocities and time differences for some common rocks and substances.
Acoustic logging has the following main applications: ① Stratigraphic division: In

sand-shale sections, sandstone exhibits low time-difference curve values because sound waves propagate quickly, whereas shale exhibits the opposite. For cements, muddy cements have the highest time difference, followed by siliceous and calcareous cements. However, as calcium content increases, the speed of sound wave propagation increases, and the time difference decreases. In carbonate formations, time difference values are generally not high. If mud is intermixed, it will slow down the sound waves and increase the time difference. If there are porous or fractured carbonate rocks, the time difference of sound waves will increase rapidly due to the presence of air, sometimes even causing cycle skips; ② Gas layer identification: In shallowly buried formations, due to the influence of gas layers, sound wave propagation encounters abrupt interfaces, causing cycle skips, which indicates a large time difference; ③ Determination of porosity.

Table 1: Longitudinal wave velocities and time differences of common rocks and certain materials

Name	Vp/(m/s)	Δt/(μs/m)
air	330	3030
clear water (well fluid)	1530～1620	654～617
steel casing	5340	187
loose clay	1830～2440	550～410
coal	2130～3350	470～300
mudstone	1830～3960	548～252
muddy sandstone	5640	177
permeable sandstone	5940	168
tight sandstone	5000～5800	200～170
tight limestone	6400～7000	156～143
dense dolomite	7000	143

3.Well logging data processing and interpretation

As oilfield exploration and development become increasingly complex, the field of well logging has accumulated a wealth of knowledge, and the requirements for the precision and difficulty of well logging data processing and interpretation continue to rise. Well logging data processing and comprehensive interpretation, including qualitative interpretation and quantitative analysis, processing, and evaluation of well logging data centered on formation evaluation, are fundamental methods and processes that run through the entire process of oilfield exploration and development [6]. A well logging processing and interpretation model refers to the objective relationship between well logging information and geological information. After understanding theoretical analysis, experimental research, and statistical data, this relationship is abstracted into images that are easy for people to comprehend [7]. Currently, the ability to analyze, interpret, and reconstruct underground geological features through well logging processing and interpretation relies heavily on the experience, skills, and judgment of well logging interpretation experts. However, experts with such experience take a long time to develop, and there is often a risk of their knowledge being lost once formed. Therefore, automation and intelligence in well logging data processing and interpretation is one of the main goals currently being explored in this field. Consequently, how to represent the vast amount of knowledge in the field of well logging processing and interpretation to facilitate rapid access to targeted knowledge in knowledge bases and achieve the sharing and reuse of domain knowledge is a significant challenge in well logging processing and interpretation [8].

At present, combined well logging interpretation results charts are mainly used to guide oil well development in oilfields. Well logging data can be used to divide the stratigraphic profile of oil and water wells, determine the thickness and burial depth of underground rock formations, identify reservoir layers and distinguish between oil, gas, and water layers. It can also be used for regional stratigraphic correlation and, in combination with other methods, to detect and study the main mineral components of the formation, as well as formation porosity, permeability, oil and gas saturation, and structural features such as formation fractures and faults, along with sedimentary environments and the distribution of ore bodies. This is of great significance for evaluating the fluid storage capacity of formations, monitoring the exploitation status of oil and gas reservoirs, and conducting detailed analysis and research on the geological characteristics of oil layers.

A lower natural gamma value indicates a better sand body. To determine whether it is an oil layer or a water layer, one must first locate the sand body on the chart, as only formed sand bodies can store oil and water. Theoretically or ideally, a sand body should resemble a box shape, but in reality, no sand body reflected on the logging curve is a standard "box-shaped" one. On the combination chart, areas with relatively high natural gamma curves indicate mudstone, while areas with low values indicate sandstone, or sand bodies. The spontaneous potential curve can effectively complement the natural gamma curve in assessing the porosity and permeability of sand bodies. The greater the leftward shift of the spontaneous potential curve, the better the sand body.

After identifying the effective sand body of the oil or water layer based on the natural gamma curve, the next step is to examine the acoustic time difference curve values corresponding to that sand body. Typically, when the borehole diameter does not expand within the sand body, a larger acoustic time difference indicates relatively better porosity and permeability of that layer. If the acoustic time difference is less than a certain value, it suggests that the identified sand body is directly a tight or dry layer.

Based on the sand bodies identified using the natural gamma curve, the resistivity values corresponding to these sand bodies are examined to determine whether they contain oil and the level of oil saturation. Higher resistivity indicates higher oil saturation, while lower resistivity indicates poorer oil saturation or the presence of a water layer. If the identified sand body has a high shale content or the corresponding acoustic time difference is too small, it may affect the resistivity, leading to misidentification of oil and water layers. The Yanchang Oilfield covers a wide area with multiple oil-bearing formations. Even within the same region and the same oil-bearing formation, there can be significant variations in resistivity, requiring years of accumulated experience to assess oil saturation. Ideally, the resistivity of an oil reservoir should be higher than that of the surrounding shale formations above and below it. However, such ideal curves are rare in practical situations.

The micro-electrode curve can be used to assess the permeability of an oil layer. The greater the separation between the micro-potential and micro-gradient curves, the better the permeability; the smaller the separation between the two curves, the poorer the permeability. This curve is generally used only as an auxiliary reference. The caliper curve can be used to determine the mud invasion status. The caliper curve is used to observe whether there is any enlargement in the wellbore trajectory, known as "bellying," and to assess the mud invasion status.

4.Characteristics of logging curves

The amplitude and various morphological combination characteristics of the logging curves in marker beds can be used to analyze the sedimentary environment of the strata. Among them, the morphology of the logging curves is of utmost importance. Different genetic markers reflect different morphologies and indicators, and different sedimentary environments necessarily correspond to different characteristics. The interpretation of sedimentary environments through logging curves mainly relies on distinguishing features from the long-spaced gamma-gamma curve, natural gamma curve, and resistivity curve.

4.1.Amplitude of logging curve

The amplitude of the curves directly reflects the grain size of the sediments, the mud content, and the sorting. Lithologies with larger grain sizes, such as glutenite, conglomerate, coarse-grained sandstone, and medium-grained sandstone, exhibit higher resistivity values. The amplitude of the resistivity curve is generally higher than that of mudstone, and the natural gamma curve shows low anomaly characteristics, with the two curves appearing approximately symmetrical. These are mainly products of high-energy environments, reflecting dam sandstone bodies along the seashore or lakeshore, which are primarily formed in strong hydrodynamic environments with thorough reworking. These lithologies have large grain sizes, low mud content, high porosity, and strong water-bearing capacity. Siltstone, sandy mudstone, and mudstone, on the other hand, have lower resistivity values and high natural gamma curve characteristics, indicating that the sediments have smaller grain sizes and were deposited in weak and stable hydrodynamic conditions. They represent floodplain facies with higher mud content, greater density, and poorer permeability. Through research and analysis of numerous borehole curves measured in this exploration area, it is found that in the main sedimentary strata, the upper non-coal-bearing strata have higher curve amplitudes overall due to their larger grain size, compared to the lower coal-bearing strata, which are dominated by siltstone, sandy mudstone, and mudstone with finer grain sizes, thus exhibiting lower amplitudes than the non-coal-bearing strata.

4.2.Logging curve shape

Bell-shaped: From bottom to top, it becomes smaller and smaller, reflecting a gradual decrease in water flow and a continuous reduction in sediment supply.

Funnel-shaped: Opposite to the bell-shaped, it reflects enhanced water current erosion and energy during the deposition of the upper part of the sand body, with coarser grains and an increasingly abundant sediment supply. The upper part of the sand body is influenced by wave reworking.

Box-shaped: The energy during the deposition process is relatively balanced, with sufficient sediment supply, stable hydrodynamic conditions, and rapid accumulation. This is characteristic of the curve for river sandbars.

Tooth-shaped: Intermittent deposition with short durations.

4.3.Smoothness of logging curves

The smoothness is a secondary change in morphology, which to some extent represents the duration of continuous reworking of sediments by hydrodynamic energy, and also reflects the abundance of sediment sources. It indirectly reflects the strength of hydrodynamic energy. A toothed curve mainly indicates intermittent depositional superimposition and alternating transgressions and regressions. A smooth curve indicates abundant sediment sources, continuous deposition, and strong hydrodynamic conditions.

5.Sedimentary facies

Logging data, compared to core and outcrop data, represent indirect information. To accurately delineate sedimentary facies (subfacies and microfacies), it is essential to integrate sedimentary facies studies from outcrops and cores to establish a logging-based sedimentary facies model. To date, there is relative consistency in the classification of facies and subfacies in sedimentary facies classification [9-10]; however, some degree of disagreement exists in the classification of sedimentary microfacies, and confusion with certain subfacies often arises in application. This paper focuses on continental sedimentary facies, analyzing the characteristics of logging-based sedimentary microfacies based on a summary of sedimentary facies classification, providing a reference for the research and application of logging microfacies in continental basins [11].

According to sedimentological principles, sedimentary facies are the material manifestations of the conditions under which sediments form. From the perspective of material manifestation, this concept of facies can encompass logging facies and seismic facies. The manifestations of sedimentary facies include facies sequence diagrams, facies association diagrams, block diagrams, and equations.

The study of sedimentary facies in oil regions primarily comprises three stages: single-well facies analysis, cross-sectional correlation facies analysis, and planar facies analysis, forming an organic combination of point-line-plane to ultimately summarize the sedimentary facies model. Single-well facies analysis primarily involves describing and analyzing vertical sections, determining stratigraphic sequences, inferring depositional processes, and subsequently summarizing the facies sequence models of different facies. Cross-sectional correlation facies analysis mainly interprets the lateral distribution and variation patterns of geological facies (involving issues such as isochronous, diachronous, and facies changes). Planar facies analysis, which is lithofacies paleogeographic analysis, allows for the understanding of the regional distribution of favorable zones for hydrocarbon generation and reservoir accumulation.

Facies indicators, which best reflect the geological characteristics of sedimentary facies, are the foundation and key to sedimentary facies analysis. Facies indicators include the geometric morphology of the facies body, lithology, sedimentary structures, paleocurrents, paleobiota, and geochemical characteristics. Describing and analyzing these facies indicators are fundamental to the process of facies analysis and interpretation. The primary approach of well logging sedimentology research is to analyze and study the logging response characteristics that can describe various facies indicators.

5.1.Geometric form of phase body

The geometric morphology of sedimentary rock bodies refers to their overall shape and size, without considering internal bedding structures. It is a function of the pre-depositional topography, depositional environment, and post-depositional geological history. Only the geometric shapes of rock bodies that form and are preserved during the depositional process have value as facies indicators.

There are two approaches to studying geometric shapes. One is a process from the whole to the part, which involves first determining the approximate morphology and distribution of various facies bodies within a region or oilfield based on seismic facies, and then conducting detailed studies on each facies body using lithofacies and log facies analysis results, thereby obtaining a more precise and comprehensive description of the seismic facies. The other approach involves comparative analysis of multi-well profiles in areas with high drilling coverage and density, leading to interpretations of the geometric shapes of facies bodies and the depositional processes. Logging technology enables detailed studies of sedimentary facies, yielding more accurate results than seismic facies. In the study of facies body geometric morphology, logging data serves as a bridge between single-well calibration and the extrapolation from points to areas. Conducting multi-well profile analysis in areas with dense logging can also predict the spatial distribution of facies bodies.

5.2.Lithology and lithofacies analysis

Lithology analysis primarily involves component and structural analysis. Lithology serves as the foundation for sedimentary facies analysis, and almost all logging methods reflect lithology or the mineral composition of sedimentary rocks based on logging data. Due to the complexity of sedimentary rock lithology, which often consists of minerals in varying proportions, coupled with the influences of pore systems and fluids, as well as interferences from layer thickness and borehole conditions, it generally requires the use of two or more lithology-porosity logging methods to achieve accurate results. Intersection techniques and modeling methods are commonly employed for this purpose.

In the process of lithology interpretation, in addition to the selection of curves and methods used, attention should also be paid to factors such as borehole diameter, fractures and voids, mud conditions, electrical phase repetition, and thin layers. Necessary corrections should be made to the interpretation results based on the degree of influence.

Using logging data to study sedimentary structures primarily involves examining grain size, shape, arrangement, sorting degree, mud content, and their vertical distribution. This is based on the close response relationship between logging physical properties and lithology. Since logging depth is time-scaled, porosity, permeability, and mud content curves can reflect the variation patterns of sedimentary energy and duration, thereby describing sedimentary structures. Due to the complexity of clastic rock lithology, different logging methods and analysis techniques need to be employed to obtain certain information about rock structures during structural analysis. For weakly cemented clastic rocks, the primary factor influencing logging responses is the grains composing the rock. Therefore, logging data can be used to study grain size, shape, arrangement, and sorting. For well-cemented clastic rocks, sorting can only be determined based on a decrease in porosity when the cement content is the same. Specifically, for weakly cemented clastic rocks, the shape of natural gamma and spontaneous potential logging curves can be used to qualitatively estimate rock grain size, and natural gamma logging values can be used to determine rock grain diameter. The grain shape of the rock, whether angular or rounded, can be determined based on the abundance of feldspar and mica in the rock. If the sandstone is very pure, it exhibits very low natural radioactivity, high porosity, and high roundness. Sandstone rich in mica has a higher dielectric constant than normal, which is caused by the strong influence of this rock component on the electric field when the electromagnetic field acts perpendicularly to the laminar composition.

The traditional method for lithology and lithofacies analysis involves using porosity logging to study mineral composition, which is implemented through crossover plots. Subsequently, methods such as photoelectric absorption index, multiple regression analysis, and nonlinear theory have been successively employed to study mineral composition.

The analysis of lithofacies has gone through stages of manual analysis, pattern recognition, multivariate analysis (including principal component analysis and cluster analysis), and intelligent analysis [12-18]. The main research includes: using fractal dimension for the classification of lithology and sedimentary facies, as well as the analysis of dynamic characteristics of basin evolution; applying principal component analysis, discriminant analysis, and Markov chain methods to analyze sedimentary facies; conducting facies and log facies research through the calculation of shale content and the analysis of electrical log characteristics; utilizing existing logging data for histogram analysis, and then calculating the type of facies by comparing the error function between the established model and the object being analyzed; fuzzy set theory and multidimensional scaling analysis techniques are also included in lithofacies analysis.

5.3.Sedimentary structure

Sedimentary structures are an important aspect of logging sedimentology research. For logging data, the macroscopic structures (bedding) formed during the sedimentary process can only be detected by imaging logging and dip logging with high vertical resolution and high sampling rate. The bedding resulting from sedimentary structures includes aspects such as bedding attitude, shape, interface characteristics, and the material structure within the interface.

5.4. Paleocurrent transport direction

The direction and development of paleocurrents are determined based on the characteristics (type, angle, pattern, distribution) and direction (degree of orientation, degree of divergence, relationship with the trend of ancient slopes and sand body geometry) of current bedding, along with corresponding logging information. Image data and high-precision dip logging data, calibrated against core observation results and regional geological context, serve as the main basis for paleocurrent analysis.

5.5 Geochemical analysis

Logging techniques such as natural gamma-ray spectrometry, litho-density logging, and induced gamma-ray spectrometry logging enable the direct measurement of more than 10 elements in rocks, enhancing our ability to identify rock composition and analyze depositional environments. Through laboratory analysis and theoretical research, the interpretation of lithological composition from logging data becomes more reasonable.

6. Conclusions

(1) Natural potential logging utilizes changes in the natural potential curve to delineate lithology; natural gamma logging employs gamma curves for lithological classification and stratigraphic correlation to determine shale content; density logging can accurately calculate porosity and then distinguish the nature of various fluids in the reservoir; and acoustic logging can be used to delineate the boundary between sandstone and mudstone and to identify gas zones.

(2) By analyzing the shape of logging curves and logging values, the geometric morphology, lithology, lithofacies, sedimentary structures, paleocurrents, transport directions, and geochemical characteristics of sedimentary facies can be determined. When using the combinational characteristics of logging curve shapes to discern sedimentary environ-ments, it is necessary to have data from planar curve combinations and to conduct a comprehensive analysis in con-junction with core, cuttings logging data, as well as structural and paleogeographic background information to improve the accuracy of facies analysis.

(3) A certain curve characteristic only reflects one aspect of sedimentary features, and conclusions about sedimen-tary types should not be drawn based solely on one characteristic. Instead, multiple curve morphological features should be utilized as much as possible, combined with geological data, to make a comprehensive judgment on sedimen-tary facies. The establishment of a logging-based sedimentary model for sedimentary facies is the foundation of logging sedimentology research. In wells or well sections where cores are absent or incomplete, the establishment of logging responses and models for sedimentary records is key to the research.

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