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Research and Discussion on the Application of Logging Technology in Geological Exploration Engineering

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Abstract: In this paper, the development history of geophysical logging technology was reviewed, the application status of logging technology in the geological exploration of hydrology, marine oil and gas, and marine natural gas hydrate was introduced, logging response characteristics and identification methods in various geological exploration projects were summarized, and the current situation and development trend of new logging technology was discussed. With the gradual deepening of complex and unconventional oil-gas exploration and development, there are an increasing number of highly deviated wells, horizontal wells, and vertical wells with complex well conditions, promoting the development of unconventional reservoir logging technology as the main logging technology at present. It is urgent to deeply explore basic logging theories, formation testing, downhole fluid analysis, petrophysical analysis and logging response experiments, accelerate the research and development of new logging technologies and equipment, improve the ability and level of logging evaluation for complex reservoirs, and effectively promote the quality and efficiency improvement of unconventional oil-gas exploration.

1. Introduction

Geophysical logging is called logging for short. Various instruments are used to measure the physical parameters of the underground rock strata during the exploration and exploitation of oil, coal, and metal ore bodies, aiming to distinguish the properties of underground rocks and fluids. Logging is mainly employed to divide water barriers and aquifers in hydrogeology, and it is primarily used for stratigraphic comparison, division of oil, gas, and water layers, and determination of important parameters (such as porosity, oil saturation, and permeability of the reservoir) in oil and gas field logging [1].

2. Development history of geophysical logging technology

In 1927, the Schlumberger brothers obtained the first logging curve in the world in the Pecherbran oilfield of France, and logging technology was developed and popularized [2-3]. From the early 1930s to the 1950s, simulation logging technologies emerged one after another, such as spontaneous potential logging, natural gamma logging, induction logging, density logging, lateral logging, and radioactive logging [4-5]. Geophysical logging technology has gradually grown from simple single-electrode measurements to integrated logging series, and it has made great progress in logging method theory, data acquisition technology, data processing and interpretation methods, and application scopes. According to the characteristics of the data acquisition system, the development of logging technology can be divided into analog logging, digital logging, digital logging, and imaging logging, and it is entering the era of network logging at present [6].

3. Hydrogeological Exploration

Geophysical logging technology serves as an important measurement method in the fields of hydrogeology, engineering geology, and environmental geology, and it plays an important role in determining the properties of rock formations, analyzing the hydraulic connection of aquifers, and detecting hydrogeology, as listed in Table 1.

Table 1: Main Geophysical Logging Functions in Hydrogeological Exploration.

Logging method	Main role
Well temperature	Measure the ground temperature and determine the water temperature at the leakage or inlet position
Borehole diameter	Detect the integrity of the well wall
Spontaneous potential	Estimate the relative size and content of shale in the formation, and determine the moisture content salinity
Natural gamma	Determine the amount of shale in the formation, and assist in dividing the spacing between water-bearing water-repellent layers
Apparent resistivity	Measure the parameters of resistivity in the formation rock, and divide the formation lithology section
Well fluid resistivity	Qualitatively determine the location and thickness of the water inflow section in the borehole

3.1. The division of the water barrier and aquifer

The effective division of aquifers and aquifers in the survey area is the basis and premise for improving the implementation efficiency of hydrogeological surveys, which are obtained by neutron logging and well fluid resistivity logging technologies. The aquifers can be easily divided by comparing the resistivity and rock density around the aquifer [7].

3.2. Logging response characteristics and identification methods

Hydrogeological logging can effectively measure hydrogeological parameters and infer karst development zones, underground aquifers, and the boundary between saline and freshwater. As an indispensable exploration method in the case of coreless drilling or insufficient coring, the exploration accuracy of hydrogeological logging is much higher than that of the ground geophysical exploration method [8-11].

3.2.1. The division of the water-resisting layer and aquifer

The first problems to be solved in hydrogeological exploration are to correctly divide water-resisting layers and aquifers, determine the thickness and horizon of aquifers, and study the relationship between them. Compared with the general surrounding rock, the aquifer has a smaller resistivity, larger voids, and smaller density. The methods of dividing the water barrier layers and aquifers and determining the thickness and horizon of the aquifers mainly include acoustic logging, neutron logging, gamma-gamma logging, well fluid resistivity logging, and apparent resistivity logging. In addition, the thermal conductivity of water is higher than that of rock, and the well temperature curve becomes steeper when affected by the groundwater temperature. Therefore, the location of the water barrier layers and aquifers can be distinguished by analyzing the variation in the well temperature curve. The velocity flow logging method is based on the theory of multilayer mixed well flow. By measuring the vertical flow velocity and transverse well diameter and converting them into the flow rate, the water output and water absorption of each section of the aquifer can be obtained to determine the location and thickness of the aquifers and other parameters.

3.2.2. Determination of the crack and mud contents

In logging, fractures are usually characterized by low density, large acoustic time difference, and small resistivity. Therefore, the shale content can be judged by the natural gamma logging value. The larger the natural gamma logging value is, the more shale is filled in the fracture. Furthermore, determining the location of mud is conducive to the division of the water-resisting layers and aquifers.

3.2.3. Investigation of karst water

Through the combination of acoustic curves and natural gamma curves, the water-bearing property of karst can be clarified. Benefitting from the determination of water content, the water-resisting layers and aquifers are divided and the location of lava in fractures is confirmed. In addition, the well diameter expands with the development of fractures and karst. The development degree of karst fractures is judged by analyzing the well-diameter curve.

3.2.4. Lithology division of drilling strata

Different rocks possess different parameters, such as porosity, resistivity, density, and wave impedance. The lithologic profile of the borehole can be divided by combining sonic logging, resistivity logging, neutron porosity, and density logging data.

3.2.5. Measurement of groundwater mineralization

There is an inverse relationship between the formation resistivity and formation water salinity. Therefore, it is recommended to calculate the salinity of the formation water by logging data. The resistivity of the formation water is obtained by analyzing the abnormal value of the spontaneous potential logging curve, and then the salinity of the formation water is determined according to the inverse relationship between the two. In this way, logging technology is applied in hydrogeology, which weakens the shortcomings of the simple use of hydrological sampling points and low accuracy [12-13].

Traditional geophysical methods, such as gravity [14-15], magnetic methods [16-17], electric methods [18-19], and earthquakes [20-21], are all suitable. However, these methods are used to infer groundwater information indirectly by obtaining physical parameters such as the density, magnetism, electricity, and elasticity of geological reservoirs. Due to the problems of nonunique interpretation results, rough spatial resolution, and inability to quantitatively detect, it is difficult to effectively evaluate groundwater-related information.

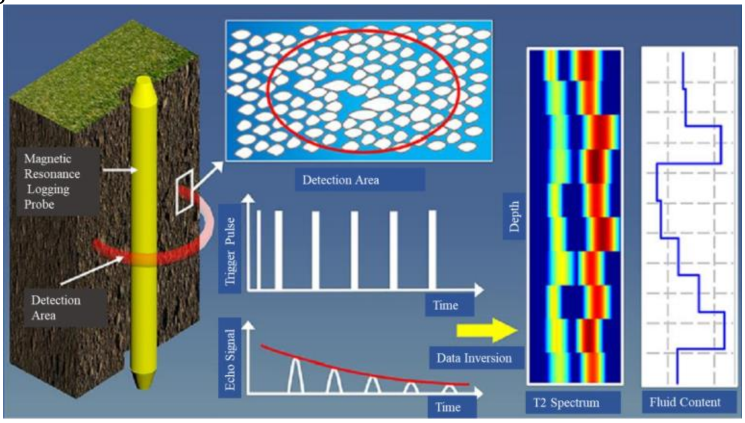

Figure 1: Schematic diagram of the hydrogeological magnetic resonance logging detection method (ZHU J B, 2022).

Hydrogeological magnetic resonance logging technology is a new geophysical method for shallow surface hydrogeological surveys. Compared with other geophysical methods, it exhibited the outstanding advantages of direct, quantitative, and efficient detection of groundwater resources [22-23]. As shown in Fig. 1, the logging probe is arranged in the monitoring wellbore, and a detection area that meets the magnetic resonance conditions is established in the surrounding formation. The principle that hydrogen protons in the fluid generate resonance-relaxation phenomenon is employed to transmit excitation pulses and receive echo signals. Invert information such as initial amplitude (E0), relaxation time (T1, T2) and fluid diffusion coefficient (D). Information on hydrogeological parameters (such as aquifer depth, water content, reservoir porosity, medium permeability, and fluid type) can be obtained separately [24]. Therefore, hydrogeological magnetic resonance logging technology realizes the direct quantitative measurement of groundwater content and proves the reserves of groundwater resources [25].The characteristic parameters of groundwater reservoirs are obtained to objectively evaluate groundwater exploitation status and provide guidance on the rational utilization of groundwater resources [26]. Moreover, this logging technology has the potential to detect pollutants mainly composed of hydrocarbons, further completing the scientific assessment of groundwater resource pollution and pollution control [27-28].

4. Oil-gas exploration geology

During oil drilling, well logging, also known as completion electrical logging, must be carried out after drilling to the designed well depth to obtain various petroleum geological and engineering technical data as the original data for well completion and oilfield development [29].

The application of logging technology in the exploration and development of oil and gas is as follows:

(1) Realize the evaluation of oil-gas reservoirs, including single-well oil and gas interpretation and fine reservoir description. The former is to divide lithology and reservoir, determine oil, gas, and water layers, and preliminarily estimate oil-gas productivity. The latter is to conduct lithological analysis and calculate porosity, permeability, and saturation [30].

(2) Carry out static reservoir descriptions and comprehensive geological research. First, the depth matching and calibration correction of logging, logging, seismic and other data are completed. Second, the vertical and horizontal changes in lithology, reservoir property, and oil-gas bearing

property of the stratum are investigated. Then, the geological structure, sedimentary facies, and source-reservoir-cap rock are further studied. Finally, the distribution rules of oil-gas reservoirs and oil-gas-water are explored, and oil-gas reserves are calculated [31].

(3) Provide a dynamic description of oil and gas reservoirs and testing data of oil and gas wells. During the development of oil and gas fields, the change rules of dynamic parameters are investigated to obtain the water flooding level of oil-gas reservoirs and the distribution status of the remaining oil-gas and analyze the injection and production profiles of production wells and their changes over time, aiming to provide basic data for improving oil-gas recovery [32].

(4) Evaluate the postdrilling quality of oil and gas wells. The sidewall coring is conducted to determine the casing running depth and cement return height. The basis for downhole operation and stimulation measures is provided, and the implementation effects are checked, such as perforation operation, perforation quality, and fracturing effect. Water, sand, and channeling layers have been explored [33].

In oil-gas exploration, conventional logging curves are capable of identifying high-resistivity oil-gas reservoirs, while low-resistivity oil-gas reservoirs and surrounding rocks cannot be identified by conventional logging curves, which is due to the similarity of their response characteristics. The combination of full-wave train logging, nuclear magnetic resonance logging, and wireline formation testing technology is an effective method for identifying low-resistivity oil-gas reservoirs and comprehensive interpretation and evaluation [34]. Compared with conventional acoustic logging, full wave logging records all acoustic wave train signals within a certain time window, including velocity, amplitude, frequency, and other information of multiple wave components (such as compressional waves, shear waves, and Stoneley waves) [35]. Parameters such as P-wave and S-wave moveout, P-wave velocity ratio, Poisson's ratio, volume compressibility coefficient, acoustic energy, and rock elastic modulus are obtained through the processing of full wave train logging data. The full wave train logging method can distinguish the oil layer, water layer, and gas layer. The gas interval changes obviously, its Poisson's ratio decreases, and its volume compressibility coefficient increases, forming an obvious intersection between the two, with a decrease in the velocity ratio of P and S waves, acoustic energy, and the elastic modulus of rocks, while the parameters of oil and water layers do not change significantly.

Nuclear magnetic resonance logging obtains movable fluid porosity [36], and its advantage over conventional logging is that it effectively distinguishes oil and water layers. In wet water formations, crude oil is a nonwetting phase fluid and also a movable fluid. The lateral relaxation time T2 of crude oil is greater than that of the water layer, and it is generally distributed in large holes. Crude oil exhibits an obvious "tailing" phenomenon in the T2 spectrum (especially light oil), while the water layer does not.

Wireline formation testing technology acquires information, such as formation pressure, temperature, and formation fluid samples. Through the relationship between logging depth and formation pressure, the formation pressure profile is established to obtain the pressure gradient. The formation fluid density is calculated from the pressure gradient, aiming to analyze the fluid properties in the reservoir and determine the gas, oil, and water interfaces [37].

5. Marine gas hydrate exploration geology

Natural gas hydrate is an ice-like solid substance formed by natural gas (mainly methane) and water under the conditions of low temperature and high pressure [38]. As a new unconventional clean energy, it has always attracted much attention. With the increasing amount of natural gas hydrates, the large-scale exploration and development of natural gas hydrates is also on the agenda, and logging evaluation of natural gas hydrates is very urgent [39].

The physical properties of the natural gas hydrate are quite different from those of the rock minerals and water, and the logging response characteristics of gas hydrate-bearing intervals are generally characterized by low gamma, low density, high porosity, high resistivity, and low acoustic time difference, especially high resistivity and low acoustic time difference [40].

In recent years, China has made important progress in the geological survey of natural gas hydrates in some areas of the South China Sea, obtaining core and logging data of subsea natural gas hydrate development layers. The Shenhu Sea area in the northern South China Sea has experienced a complex tectonic evolution process with developed faults, in which the vertical distribution of gas hydrate has obvious discontinuity and heterogeneity [41]. Based on a summary of previous research results [42-45], the logging response characteristics of natural gas hydrate reservoirs in the Shenhu Sea area of the South China Sea are as follows.

(1) Caliper logging: hydrate is largely decomposed in the ordinary drilling process, rock stability is destroyed, and borehole diameter is significantly expanded compared with other horizons. However, the diameter curve of the natural gas hydrate reservoir section in the Shenhu Sea of the South China Sea did not change significantly.

(2) Spontaneous potential logging: the solid hydrate blocks the pore space of the reservoir and reduces diffusion and percolation, and the spontaneous potential presents a negative anomaly.

(3) Natural gamma logging: gas hydrate absorbs a large amount of water molecules from the upper and lower strata and hydrocarbon gas from the underlying sediments during the formation process, resulting in a relative reduction in clay content per unit volume of sediments. The curve is characterized by a sudden decrease.

(4) Acoustic time difference logging: the longitudinal wave offset time of gas hydrate is approximately 80 μs/ft, which is greater than that of quartz (55 μs/ft) and obviously less than that of water (190 μs/ft) and natural gas (more than 200 μs/ft). The logging curve shows a decreasing feature (1 ft=30.48 cm).

(5) Density logging: the density (approximately 0.91 g/cm3) curve of hydrate-bearing formations is obviously lower than that of non-reservoir, slightly lower than that of completely saturated water (1 g/cm3), and quite different from that of natural gas (0.1~0.2 g/cm3).

(6) Resistivity logging: the conduction of current in rocks is mainly realized by the movement of ions in pore water. The migration channels of ions are blocked when the pores of rocks are filled with gas hydrate, which leads to an increase in rock resistivity. The logging curve exhibits the characteristics of increase.

(7) Logging of the pore water chloride concentration: the natural gas hydrate is decomposed in the presence of mechanical friction during drilling, and the released fresh water dilutes the salinity of the pore water, leading to a reduction in the chloride concentration in the pore water.

Lithology interpretation is the basis of hydrate reservoir evaluation. Conventional lithological interpretation is mainly determined by natural gamma [46-47], neutron porosity, and density. In the Shenhu area of the South China Sea, the logging data of individual well locations during drilling showed that the natural gamma value of the upper gas hydrate and its upper layers is obviously low. The core test results displayed that the quartz content in the low gamma layers has not increased significantly. The uncertainty of the lithologic profile obtained only by using conventional logging projects is too strong to calculate the carbonate content of the accurate formation [48]. Elemental capture spectroscopy logging provides intuitive mineral types and contents, so it can be directly applied to evaluate formation lithology. Han Lin et al. used elemental capture spectroscopy logging to accurately identify igneous rock lithology [49]. Yuan Zugui et al. reported that the reservoir lithology of the Wangzhuang Oilfield was explored using elemental capture spectroscopy logging [50]. Kang Dongju et al. used the lithologic results obtained by elemental capture spectroscopy processing as the input of ElanPlus [51] processing, and the lithologic profile of complex well locations was determined by combining other conventional logging data. The porosity, hydrate saturation, and matrix permeability of the hydrate layer were estimated based on the mineral components obtained from elemental capture spectroscopy, which provides a new means and method for the comprehensive evaluation of hydrate reservoirs and improves the coincidence rate of hydrate reservoir logging interpretation [52].

Qin Xuwen and Kang Dongju et al. found evidence of an abnormal decrease in chloride concentration from the coring data of the Shenhu Sea area in the South China Sea [53-54], thus confirming the coexistence of hydrate and free gas. Based on LWD data and coring analysis data, Xie Yingfeng et al. used the core calibration logging method to evaluate the three-phase mixed layer of hydrate, free gas, and water in the Shenhu Sea area and qualitatively identified the three-phase mixed layer. The specific characteristics are as follows: compared with the hydrate layer, the density and neutron porosity values of the three-phase mixture layer of hydrate, free gas, and water decreased, and the longitudinal wave velocity decreased; compared with the gas reservoir, the shear modulus of the three-phase mixed layer was still greater than the background value, and the concentration of chloride ions in core pore water decreased [55].

6. Conclusions and Suggestions

(1) Geophysical logging technology has been widely and successfully applied in the field of hydrogeological exploration and has gradually become an indispensable exploration method. To improve the reliability of the horizontal and vertical interpretation results of hydrogeological exploration, the combination of different logging methods should be studied in the next step.

(2) Well logging technology has been widely used in the whole process of exploration and development of the oil and gas fields, playing a crucial role in oil and gas resource evaluation and reservoir management. This paper analyzed the application and effect of well logging technology from its concept and development trend, which provides basic support for future research on the automation and intelligence of oil and gas exploration.

(3) The logging response characteristics of natural gas hydrate reservoirs are as follows: the change in well diameter is not obvious, the natural potential presents a negative anomaly, the natural gamma radiation decreases, the acoustic transit time decreases, the density decreases, the resistivity increases, and the chloride concentration in pore water decreases. Natural gas hydrates are considered to be an important alternative resource for fossil fuels in the 21st century, especially in the Shenhu Sea area of the South China Sea with great exploration potential and broad development prospects. Logging evaluation technology for complex hydrate reservoirs is rarely studied at present. Whether complex hydrate reservoirs can be identified and refined quantitatively is the focus of current and future research on gas hydrate exploration technology.

(4) With the gradual deepening of complex and unconventional oil-gas exploration and development, there are an increasing number of highly deviated wells, horizontal wells, and vertical wells with complex well conditions. Unconventional reservoir logging technology has become the main technology of current logging. It is urgent to deeply explore basic logging theories and formation testing, downhole fluid analysis, petrophysical analysis, and logging response experiments, realize intelligent identification and dessert evaluation of oil-gas reservoirs, accelerate the research and development of new logging technologies and equipment, improve the ability and level of logging evaluation to solve complex reservoirs, and effectively promote the quality and efficiency improvement of unconventional oil-gas exploration.

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