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Development and implementation of «logging-while-drilling» technology in Ukraine. Methods and tools for determination of petrophysical parameters of reservoirs while drilling vertical, deviated, and horizontal oil-and-gas boreholes

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Logging-while-drilling (LWD) oil-and-gas boreholes is an advanced technology that improves the efficiency of drilling-and-logging operations. The cost of services and the

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technological monopoly of foreign firms, and their leaving from Ukraine in 2022, make urgent the development of domestic apparatus-and-methodological complexes for LWD. The Group of Nuclear Geophysics of the Institute of Geophysics of the NAS of Ukraine, together with LLC «Ukrspetsprylad», have created a number of methods and tools for determining the petrophysical parameters of reservoirs during LWD. The effectiveness of the developments has been confirmed by borehole tests and comparison with independent data.

Key words: oil-and-gas borehole, logging-while-drilling, combination of logging methods, set of apparatus devices, interpretation methodology, petrophysical parameter.

Introduction. Logging-while-drilling (LWD) is an advanced technology in geophysical well logging used to determine the petrophysical and other parameters of rocks during drilling vertical, deviated, and horizontal oil-and-gas boreholes.

Western companies began commercial implementation of LWD technology in the late 80's — early 90's of the twentieth century. Leading companies have achieved significant results in the field of LWD and its wide application. Modern LWD systems are ultimately designed not only to minimize traditional geophysical surveys (logging after drilling vertical and moderately deviated boreholes) but also allow to expand their usage to deviated (deviation angle greater than 50°) and horizontal boreholes.

The main factors that have stimulated the development of LWD measurements include: a significant reduction in cost and a general increase in the promptitude, effectiveness, and productivity of drilling-and-logging operations, a significant increase in hydrocarbon production in horizontal boreholes, as a result of which their proportion has grown greatly; favorable conditions for obtaining petrophysical parameters — centered system of measurement (standoff), practically no influence of invasion, mud cake and colmatation, minimal influence of rugosity, increased statistical accuracy of radioactive logging (RL), transmission of the necessary parameters in real time.

In Ukraine, non-traditional drilling was insignificant in volume. LWD was based on expensive services of foreign companies. At the same time, they do not share either information about the features of the apparatus or the interpretation methodology with consumers. With the beginning of a full-scale war, these works were stopped, and the equipment was removed. Thus, it is necessary to develop and implement domestic apparatus-and-methodical complexes of LWD.

Since 2017, the Institute of Geophysics of the National Academy of Sciences of Ukraine (IGPh) partnered with LLC «Ukrspetsprylad» (USP) to create and implement an original RL module for the LWD survey under a scientific-and-technical partnership agreement. Recently, the LWD combination of «RL+induction-type logging (ITL)» has been developed to extend the set of petrophysical parameters important for practice.

Work on metrological support of the RL module is carried out on the created full-scale models of reservoirs; new methods for determining petrophysical parameters and corresponding devices are being developed; the methodology for interpreting LWD measurements is being improved. Testing of the developments is carried out in horizontal and vertical oil boreholes; the LWD results are confirmed by comparison with logging data run by well-known companies in same but uncased boreholes.

A number of the obtained results have been published as articles, patents, patent applications, and reports at international conferences (see References).

Subject and methods of investigation when LWD. Features of LWD measurements. The subject of investigation in LWD are rocks in the section of oil-and-gas boreholes; more specifically, it is the petrophysical parameters of oil and gas reservoirs while drilling. The employed logging methods allow to measure through special thick-walled steel drill pipes. In our developments, radioactive logging (RL) is used, namely gamma-ray logging (GR), neutron-neutron logging (NNL), neutron-gamma logging (NGL), gamma-gamma logging (GGL), as well as induction-type logging (ITL) (through non-magnetic pipes).

During LWD measurements, the logging sensors are in special drill pipes of different diameters and wall thicknesses (drill collar, DC). Drill collars are located immediately behind the drilling system and have an increased diameter compared to the next string of drill pipes.

Transmitters and receivers of high-frequency electromagnetic waves are mounted in the DC (prepared based on steel (at the first stage) or non-magnetic steel pipes) closest to the bit for making induction-type measurements (propagation resistivity), as well as a sensor of natural gamma-ray and other devices for measuring drilling parameters (measurement-while-drilling, MWD). The MWD system is used, in particular, for navigation in horizontal formations (geosteering). The LWD system with RL devices (usually NNL, GGL) built-in the DC is right behind. The devices are used to obtain the parameters of oil and gas reservoirs while drilling.

Individual logging methods for LWD. ***Parameters of shaliness***. Shaliness is an important lithological property; it should also be taken into account when obtaining petrophysical parameters using logging methods. To determine the *shale content* of terrigenous rocks, empirical relationships between shale material according to laboratory data and GR readings are most often used. We proposed a method for quantitative estimation of the *content of clay minerals (clay)* based on GR [Bondarenko, Kulyk, 2024] to improve the accuracy of estimating the reservoir properties, particularly the total porosity based on NNL data.

The *gamma-ray index* is an interpretation parameter of the GR. Using numerous borehole examples, it was proved invariant for a given borehole section at open-hole logging and in the presence of a steel (drill or casing) string. GR index is also practically independent of the borehole diameter, etc. Taking this into account, the corresponding dependencies for determining the shale and clay contents with the help of the GR are universal, and we use them during LWD [Bondarenko, Kulyk, 2024].

LWD propagation resistivity. An elementary sonde (array) for the ITL consists of one transmitter (T) and two receivers (R). The latter are relatively close to each other and together are the sensor of the tool; the distance between the midpoint of the two R and the T serves as the sonde spacing. The compact ITL tool for LWD consists of two R and two T, i.e., it uses two sonde spacings (60 cm and 100 cm long). The frequencies of electromagnetic wave radiation are 2 MHz and 400 kHz.

We operate with the resistivity of rocks obtained by measuring the **p**hase **s**hift of waves propagated in the rock (propagation resistivity, R_{ps}, Om·m). Thus, the ITL tool for LWD makes it possible to obtain four R_{ps} parameters (for two sondes and two frequencies) with different, high enough (in the order of 75 cm), depths of investigation. This provides for high informativity of the ITL when LWD.

Combination logging methods for LWD. ***Total porosity of reservoirs.*** The NNL method is implemented as compensation neutron logging (CNL), which uses the ratio of neutron detector readings at two source-detector spacings to determine *neutron porosity*. Moreover, the CNL significantly reduces the influence of a number of factors: mineralization of pore fluid, borehole parameters and its filling, the tool, etc.

In low-shaly water-oil reservoirs, neutron porosity is close to the true one. In the general case of shaly reservoirs, the porosity determined by the CNL is apparent one due to the hydrogen in clay minerals. To determine the *total (true) porosity of water-oil reservoirs* based on CNL for LWD, we proposed to make a correction for the hydrogen index of clay minerals using GR (CNL+GR) [Kulyk, Bondarenko, 2024].

For gas-saturated reservoirs, the total (true) porosity by CNL+GR is underestimated due to the reduced amount of hydrogen per unit volume of rock, and the porosity by GGL_D is overestimated due to the reduced total density of the reservoir. Determining the total porosity of gas-saturated reservoirs is only possible by combining these two approaches. We have developed a method for determining *the true porosity of gas-saturated formations* as the weighted mean of the porosities by CNL+GR and GGL_D (with appropriate weighting factors) [Bondarenko, Kulyk, 2017].

Density of rocks. The set of RL methods for LWD measurements usually includes *gamma-gamma logging to obtain rock density* (GGL_D). The disadvantage of the traditional implementation of GGL_D during LWD is the disregard for the influence of the natural gamma-ray of rocks on the readings of the 2GGL tool, which can lead to significant errors in the determined density. To more accurately determine the *density of reservoirs by* GGL_D for LWD, we proposed to make a correction for gamma-background (GB) [Kulyk, Bondarenko, 2024].

The wall thickness of the drill collar must be limited due to the shallow depth of the GGL_D method (~ 12 cm) for its effective usage. The LWD conditions of horizontal boreholes and a ^{60}Co gamma source in the $2GGL_D$ tool meet these requirements [Kulyk, Bondarenko, 2023].

To determine the density of rocks during LWD of all types of boreholes without restrictions on the diameter and wall thickness of the DC, we proposed a *method of neutron-gamma density logging* (NGL_D). The NGL_D method has the maximum possible depth of investigation of RL methods (several times greater than the GGL_D). The contribution of GB to the readings of the $2NGL_D$ (or $1NGL_D$) tool is subtracted. The influence of the clay content of rocks, which essentially underestimates their density by NGL_D, can be eliminated using our correction semi-empirical formula that takes into account the content of clay minerals, porosity, and lithotype of the rock [Kulyk et al., 2023; Kulyk, Bondarenko, 2024].

Oil and gas saturation factors. Resistivity R_{ps} (propagation resistivity) is closely, although in general not simply and ambiguously, related to other petrophysical parameters of reservoirs — shaliness, effective porosity, density, lithology, etc. For example, the *oil saturation factor* S_o is determined through the parameter R_{ps} for a given porosity and low shale content. Interestingly, according to LWD measurements in carbonate oil-saturated formations, there is a correlation between porosity and the factor S_o: the higher the porosity, the higher the S_o.

According to the method we have developed, *the gas saturation factor* S_g can be obtained using the CNL+GR+GGL_D combination as a value that is proportional to the ratio of the difference in density and neutron porosities to the true porosity determined by the same combination [Bondarenko, Kulyk, 2017].

Apparatus modules for LWD. The IGPh and USP have proposed several fundamentally new approaches to creating devices for the MWD and LWD systems. Instead of mounting the devices in each DC, universal modules of small diameter are used. The modules are inserted into the corresponding DC before carrying out work. Besides, in the LWD system, the RL module is supplemented with an NGL device and gamma-background detector (GB) (aka as a gamma-ray logging detector) [Bondarenko et al., 2019, 2023; Danyliv et al., 2021, 2022; Kulyk, Bondarenko, 2021, 2023]. An addition to the LWD system with the compact device of induction-type logging (ITL) is being developed, too. These LWD systems allow for a much more accurate and extensive determination of petrophysical parameters of oil and gas reservoirs based on individual methods (GR, ITL) and using combinations (CNL+GR, GGL_D+GB, NGL_D+GB+GR, CNL+GR+GGL_D, RL+ITL).

Examples of using the author's developments (methods, tools, interpretation methodology) while drilling horizontal boreholes have shown their high technological effectiveness and efficiency. The parameters of the reservoirs obtained when LWD are confirmed by independent measurements by the PEX tool (Schlumberger) in the same open boreholes after drilling [Kulyk, Bondarenko, 2023].

Conclusions. The results show the potential of the developed methods, devices, and methodology for LWD in Ukraine. An important factor is that domestic inventors have the necessary set of ideas and know-how and all the opportunities to improve the development and adapt it to specific requirements and subsequent implementation.

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Розвиток і впровадження в Україні технології «каротаж в процесі буріння». Методи і пристрої для визначення петрофізичних параметрів колекторів при бурінні вертикальних, похилих і горизонтальних нафтогазових свердловин

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Каротаж в процесі буріння (logging-while-drilling — LWD) є передовою технологією, яка підвищує ефективність бурильно-каротажних робіт. Вартість послуг і технологічна монополія іноземних фірм, а у 2022 р. — їхній вихід з України, актуалізують розробку вітчизняних апаратурно-методичних комплексів LWD. Групою ядерної геофізики Інституту геофізики НАН України разом з ТОВ «Укрспецприлад» створено ряд способів і пристроїв для визначення петрофізичних параметрів колекторів при LWD. Ефективність розробок підтверджена свердловинними випробуваннями і порівнянням з незалежними даними.

Ключові слова: нафтогазова свердловина, каротаж в процесі буріння, комплекс методів, сукупність апаратурних пристроїв, методика інтерпретації, петрофізичний параметр.