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GEOPHYSICAL INTERPRETATION METHODS' IMPROVEMENT OF BILCHE-VOLYTSKA ZONE OF PRE-CARPATHIAN FOREDEEP COMPLEX GEOLOGICAL CROSS-SECTIONS' COMPREHENSIVE RESEARCH RESULTS

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Розглядається проблема, пов'язана з неоднозначністю результатів комплексних геофізичних досліджень свердловин (ГДС), що відбивається у зниженні ефективності інтерпретаційних методик окремих методів і, як наслідок, у пропуску нафтогазонасичених порід-колекторів. У зв'язку з цим проведено аналіз результатів гамма-каротажу, методів самочинної поляризації, ядерно-магнітного каротажу. Отримана інформація експериментальних досліджень керну дозволила встановити причини викривлення показів радіоактивного та електричного каротажів, які значно впливають на величину інтенсивності радіоактивного та електричного полів. Також проведено обґрунтування ефективності гамма-спектрометричного методу та ядерно-магнітного резонансу. Встановлено, що у складі матриці порід неогенових відкладів наявні мінерали сульфідів, окислів, до складу яких входять залізо, мідь, алюміній, що обумовлює електронну провідність нафтогазонасичених пластів. За результатами гамма-спектрометрії у матриці вказаних вище порід визначено відмінні від кларкових вмісти урану, торію та калію, які впливають на величину природної інтенсивності радіоактивного поля насичених вуглеводнями порід. Для однозначної оцінки природи підвищеної радіоактивності порід неогенових відкладів розроблено методику визначення кларкового вмісту радіоактивних ізотопів урану, торію та калію з розрахунком їх співвідношення. Наведено результати обґрунтування застосування новітніх технологічних методів гамма-спектрометрії та ядерно-магнітного резонансу під час виділення продуктивних порід. Свердловинні дослідження методом ЯМР ефективно можна провести за допомогою АЯМК-3 – апаратури ядерно-магнітного каротажу, а гамма-спектрометрію – за допомоги апаратури СГСМ-2.

Ключові слова: гамма-спектрометрія кернового матеріалу, іонна та електронна провідність, кларковий вміст радіоактивних ізотопів, магнітний резонанс.

Рассматривается проблема, связанная с неоднозначностью результатов комплексных геофизических исследований скважин (ГИС), что отражается в снижении эффективности интерпретационных методик отдельных методов и, как следствие, пропуске нефтегазонасыщенных пород-коллекторов. В связи с этим проведен анализ результатов гамма-каротажа, методов спонтанной поляризации, ядерно-магнитного каротажа. Полученная информация экспериментальных исследований керна позволила установить причины искривления показаний радиоактивного и электрического каротажей, которые значительно влияют на величину интенсивности радиоактивного и электрического полей. Вместе с этим проведено обоснование эффективности гамма-спектрометрического метода и ядерно-магнитного резонанса. Установлено, что в матрице пород неогеновых отложений присутствуют минералы сульфидов, окислов, в состав которых входят железо, медь, алюминий, наличие которые обусловливает электрическую проводимость нефтегазонасыщенных пластов. По результатам гамма-спектрометрии в составе матрицы выше указанных пород выявлены отличные от кларковых содержания урана, тория и калия, которые определяют величину естественной интенсивности радиоактивного поля насыщенных углеводородами пород. Для однозначной оценки природы повышенной радиоактивности пород неогеновых отложений разработана методика определения кларкового содержания радиоактивных изотопов урана, тория и калия с рассчитанными их соотношениями. Приведены результаты применения новейших технологических методов гамма-спектрометрии и ядерно-магнитного резонанса при выделении продуктивных пород. Скважинные исследования методом ЯМР эффективно можно провести с помощью АЯМК-3 – аппаратуры ядерно-магнитного каротажа, а гамма-спектрометрию – с помощью аппаратуры СГСМ-2.

Ключевые слова: гамма-спектрометрия кернового материала, ионная и электронная проводимость, кларков содержание радиоактивных изотопов, магнитный резонанс.

The article considers the problem related to the ambiguity of logging results, which is reflected in the reduction of the efficiency of certain interpretive methods, and as a consequence of oil and gas reservoirs omission. In this regard, the analysis of the results of gamma logging, spontaneous polarization methods, nuclear magnetic logging, were conducted. The received information of experimental researches of cores, has allowed establishing the reasons of distortion of radioactive and electric logging indications which considerably influence on size of radioactive and electric fields intensity. In addition, the efficiency of gamma-spectrometric method and nuclear magnetic resonance is substantiated. It is established that the matrix of rocks of Neogene sediments contains minerals of sulfides, oxides, which include iron, copper, aluminum. That determines the electronic conductivity of oil and gas saturated layers. Different from clarke, the contents of uranium, thorium and potassium were determined in the matrix of the above mentioned rocks according to the results of gamma spectrometry. These elements affect the value of the natural intensity of hydrocarbon-saturated rocks' radioactive field. A method for determining the carke content of radioactive isotopes of uranium, thorium and potassium with the calculation of their ratio was developed to unambiguously assess the nature of the increased radioactivity of Neogene rocks. The results justify the use of the latest technological methods for gamma spectrometry and nuclear magnetic resonance in the allocation of productive rocks. Well research by NMR can be effectively performed with the help of NMLE-3 (nuclear magnetic logging equipment), and gamma spectrometry can be conducted with the help of SGSM-2.

Key words: gamma spectrometry of core material, ionic and electronic conductivity, clarke content of radioactive isotopes, magnetic resonance.

Introduction

Increasing hydrocarbon production in Ukraine involves the development and introduction into production of new promising methodological and technological tools based on modern advances in science and technology. The analysis of the geological structure of lithological and stratigraphic strata of prospecting and exploratory wells of the Bilche-Volytska zone of the Pre-Carpathian Foredeep showed that in each case there are peculiarities both in the structure of the rock matrix and in the conditions of its formation. It can be stated that the Sarmatian, Baden and Helvetic stages are the most promising rock complexes for hydrocarbon production in the Neogene system. The complexity of the geological structure of the Neogene system is caused by the rhythmicity and fine layering of the sand-clayey layers, as well as the lack of reliable marker horizons when performing correlation constructions.

Analysis of published works

In articles [1, 2] the theoretical aspects of nuclear physics methods, in particular nuclear magnetic resonance and gamma spectrometric researches conducted in classical geological cross-sections with ideal conditions for the formation of hydrocarbon deposits, are substantiated in detail. Given the complicated structure of lithological and stratigraphic strata of Neogene deposits of the Bilche-Volytska zone of the Pre-Carpathian Foredeep, it is necessary to adapt the theoretical foundations of nuclear physics methods to specific geological cross-sections of oil and gas-saturated reservoir rocks.

Coverage of previously unresolved parts of the overall problem

An unambiguous characteristic of the lithotypeis not always obtained in the process of research of complexly constructed cross-sections by a standard set of logging. This ultimately leads to the omission of oil and gas saturated rocks. Therefore, taking into account the peculiarities of the geological structure of lithological and stratigraphic strata of the Bilche-Volytska zone of the Pre-Carpathian Foredeep, it is necessary to substantiate the methodological development, as well as the introduction of new nuclear physics methods and applied guidelines in the complex of logging.

Objectives of the article

To substantiate the efficiency and reliability of the latest technologies on the example of geological cross-sections of gas and condensate fields of Bilche-Volytska zone of the Pre-Carpathian Foredeep. In particular, the efficiency and reliability of nuclear magnetic resonance and gamma spectrometry in the process of complex geophysical research will be considered in more detail.

The main tasks

To perform a comprehensive analysis of geological and geophysical surveys that were conducted in wells of gas and condensate fields with complex geological structure within the Bilche-Volytska zone of the Pre-Carpathian Foredeep. The second task is to substantiate the optimal set of geophysical surveys for unambiguous determination of reservoir rocks and to assess the saturation nature in cases of complex geological structure.

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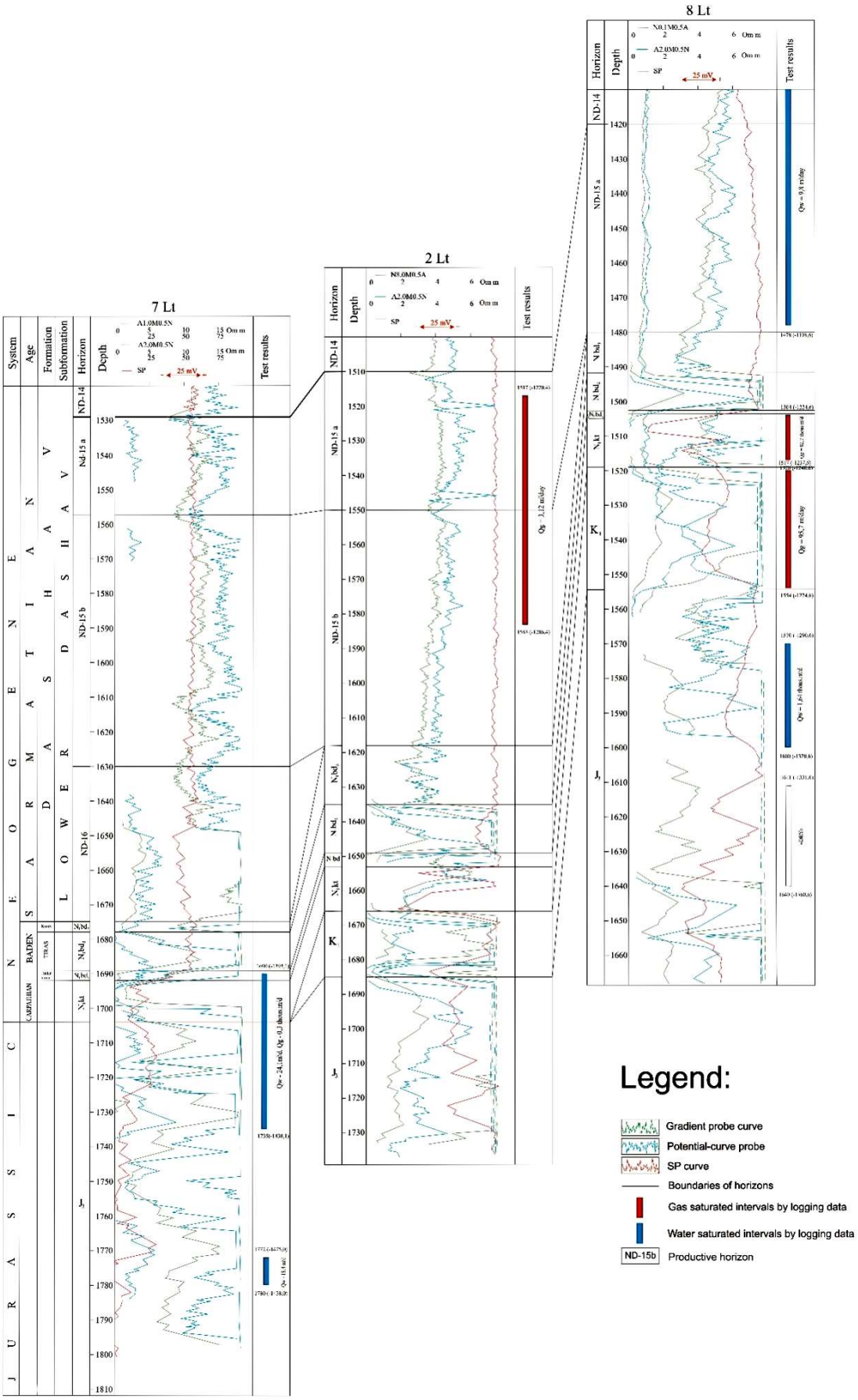

Figure 1 – Correlation scheme of the productive part of Neogene sediments constructed by the results of electric logging in wells №№7-2-8 of Letnyansky gas field

Table 1 – Mineralogical composition of the rock matrix according to the results of petrography and gamma spectrometric analysis

Depth of core selection, m	Lithological characteristics of rocks	Minerals that contain radioactive elements	The content of radioactive isotopes, %		
			$Th \cdot 10^{-4}$	$U(Ra) \cdot 10^{-4}$	K
Well No 2					
1673,5	Gravels and stone with chlorite-clayey cement	zircon - 1%, chlorite – up to 5%	2,5	1,3	0,8
1674	Gravelly-sandy limestone	chlorites - (3-5%), accumulation of phosphorites with red fragments of chalcedony	2,5	1,3	1,4
1675,2	Fine-graineds and stone with glauconite and chloride-clayey cement	zircon – 1 %, glauconite – 0,5 %	2,8	1,7	0,7
Well No 5					
1588,5	Gravel-sandy siltstone	zircon - (1-1,7)%, clayey and carbonat ecement	2,3	0,9	0,2
1590,0	Sandy limestone with remains of foramifer	single grains of glauconite - 0.6%, pyrite, clayey and carbonate cement	2,5	1,4	0,4
1592,0	Fine-graineds and stone with chloride-clayey cement	singles grains of zircon, staurolite and chamosite	3,2	1,4	0,3
1593,0	Medium-graineds and stone with calcite cement, single grains of glauconite	glauconite – (1-1,2) %	2,1	1,1	0,3
1596,0	Gravels and silt stone with clayey-chlorite and clayey cement	zircon - 1.1%, chlorites - 3.1%, effusive clay - 1.4%	1,8	0,01	0,1
Well No 9					
1484,0	Siltstys and stone with clayey-calcite cement	single grains of glauconite	1,8	2,8	0,3
1482,1	Fine-graineds and stone with calcite cement, foraminifera and single glauconite	single grains of glauconite, marcasite, organic seaweed	3,7	1,3	1,4

The main material of the research

It should be noted that the complex geological structure of rocks causes difficulties in unambiguous identification of reservoir rocks, assessment of the saturation nature, as well as leads to the omission of a significant number of gas and condensate objects. Insufficient informativeness of typical complexes of geophysical methods (in particular electric and radioactive surveys), which were carried out in clayey lithological cross-sections that are characterized by significant fine-rhythmic alternation of different lithotypes, distinguishes those strata as homogeneous physical objects (so-called "barren strata").The morphology of geophysical curves is represented as a straight line despite the interbedding of rocks with different lithological and physical parameters (Fig. 1).

Analysis of the results of complex laboratory core studies (objects from which core was selected are represented in table 1) allowed to optimize the results of geophysical studies. Also, this analysis made it possible to focus on the informative possibilities of the latest methods, including nuclear magnetic resonance (NMR), gamma spectrometry and gamma logging using the collimation of the NaJ (Te) radiation intensity indicator.

The obtained results of laboratory researches allowed to state that the increased radioactivity of the rocks of the Sarmatian, Baden and Helvetic agesis mainly caused by the polymineral structure

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of the matrix. The matrix includes such minerals as zircon, chlorites, phosphorites. High electrical conductivity in most of the above mentioned rocks is caused by accumulations of pyrite, staurolite, chamosite and increased mineralization of formation waters (75%, NaCl).All the above mentioned factors that characterize the productive deposits of the Neogene system create a complex system of inhomogeneous reservoir, which is difficult to determine by the traditional logging set.

The development of the latest methods and technologies (in particular nuclear magnetic research) allows obtaining reliable information in geological conditions, which are typical for the Bilche-Volytska zone of the Pre-Carpathian Foredeep. The physical essence of the nuclear-magnetic method consists in resonant absorption, and as a consequence, in the radiation of electromagnetic energy by the rock, which is caused by the transient migration of electrons between the energy levels of atomic nuclei in rocks [1, 3].According to NMR theory, an atomic nucleus with spin (J) within a magnetic field with intensity (H) has a specific number of evenly spaced levels (2J + 1) with energy depending on the distance between them:

$$\Delta E = \mu \frac{H_o}{J} , \qquad (1)$$

where ΔE - the energy difference between specific levels, *J*;

H_o - magnetic field strength of the medium, $A \cdot v/m$;

μ - the magnetic moment of the spin of the atomic nucleus, $A \cdot m^2$.

The value μ is calculated through the ratio:

$$\mu = \gamma \frac{hJ}{2} , \qquad (2)$$

where γ - gyromagnetic ratio, $s \cdot A \cdot kg^{-1}$;

h - Planck constant, $J \cdot s$;

J - number of spins in the atomic nucleus.

Based on the above, it can be assumed that nuclear magnetic methods are extremely informative for solving geological and geophysical problems that arise in the process of geophysical research of wells that are allocated within areas of complex lithological and stratigraphic conditions. Taken into account the ambiguity of the reservoir rocks determination within this type of cross-sections of the Bilche-Volytska zone, as well as the fact that the maximum value of the gyromagnetic ratio ($\gamma = \frac{\mu}{P}$, where μ is the magnetic moment, $A \cdot m^2$; P is the mechanical moment) is mainly characteristic of hydrogen atoms, which is almost 100% present in lithological-stratigraphic strata. The use of nuclear magnetic resonance parameters, in particular the time of longitudinal and transverse relaxation (T_1, T_2), the amplitude of the free precession signal (A_{fps}) is an informative criterion that significantly increases the informativeness of complex geophysical researches. The process of establishing the magnitude of the nuclear magnetization vector is called nuclear magnetic relaxation, which occurs in rocks during the exchange of nuclear moments between themselves and the environment. In this process, spin-spin and spin-lattice relaxation are distinguished. Spin-spin relaxation determines the rate of change of the induced nuclear-magnetic field, perpendicular to the component of the rock's magnetic magnetization vector, in the direction of the Earth's magnetic field.

Spin-lattice relaxation characterizes the change in the magnitude of the longitudinal relaxation amplitude with respect to the magnetization vector of the crystal lattice. In this case, the rate of change in time of the nuclear magnetization vector $\vec{M}$ with the magnitude of the Earth's magnetic field is determined. The abovementioned magnetic effects are used in the process of well and ground surveys by applying a high-frequency electromagnetic field H_{exc} on rock, which is allocated within the natural magnetic field of the Earth. The exciting, high-frequency magnetic field with an intensity of H_{exc} is much larger than the natural field, and due to this, the corresponding amplitude of the free precession signal appears in the resonance region. This amplitude decreases to the level of the magnetization amplitude of the rock under the action of the natural magnetic field H_o as the excitation field H_{exc} is excluded. Thus, the use of the latest technology of nuclear magnetic logging allows identifying the saturated layers within the geological cross-section and to assess their nature of saturation by the parameters of the longitudinal and transverse relaxation time (T_1, T_0).The amplitude of the free precession signal (A_{fps}) value unambiguously allows to distinguish sandy, siltstone rocks within clayey rocks and to assess their porosity.

Substantiation of efficiency of the newest nuclear-magnetic surveys during geological-technological researches was based on determinations of petrophysical parameters (porosity and permeability) influence on amplitude of the free precession signal (A_{fps}), relaxation time (T_1, T_2) and speed of longitudinal relaxation (r_s) in rocks with different saturation nature. An informative sample of the core material was formed for this purpose (n=141). The core material was not extracted, but was saturated with mineralized solutions of 75 g / l NaCl. The core was selected for

Table 2– The reservoir rocks` research results of the Letnyansky gas field

No	No well.	Coresampling interval, m	$K_{poros.o.}$, %	$K_{perm.}$, 10^{-15} mcm	FFI, %	T_1, msec	T_2, msec
1	2	1250,8-1261,5	23,1	3	18,7	650	84
2	2	1250,8-1261,5	20,6	175	12,9	639	57
3	2	1250,8-1261,5	21,6	9	13,7	638	60
4	3	1195,0-1215,0	23,1	-	12,0	637	56
5	3	1240,0-1250,0	23,1	153,9	17,6	670	59
6	5	1246,0-1262,0	20,3	94,1	13,7	642	61
7	5	1300,0-1316,0	21,2	103	12,1	629	72
8	5	1316,0-1332,0	23,0	7,3	15,2	632	62
9	5	1316,0-1332,0	23,2	4,8	15,5	641	63
10	5	1430,0-1446,0	17,7	-	10,5	504	59
11	7	1458,1-1465,2	18,2	0,27	10,2	581	98
12	7	1465,2-1558,1	18,0	48,4	15,2	588	92
13	7	1472,0-1478,9	4,8	-	0	260	69
14	7	1458,1-1465,2	6,7	-	0,89	264	70
15	7	1472,0-1478,2	20,7	7,0	15,4	648	72
16	7	1497,1-1503,0	5,8	-	0	252	68
17	7	1503,0-1506,9	14,9	1,75	8,8	312	51
18	9	1158,0-1168,0	25,1	-	21,6	642	62
19	9	1208,0-1216,0	22,4	3,8	16,2	638	65
20	9	1250,0-1260,0	10,3	3,72	4,2	300	54

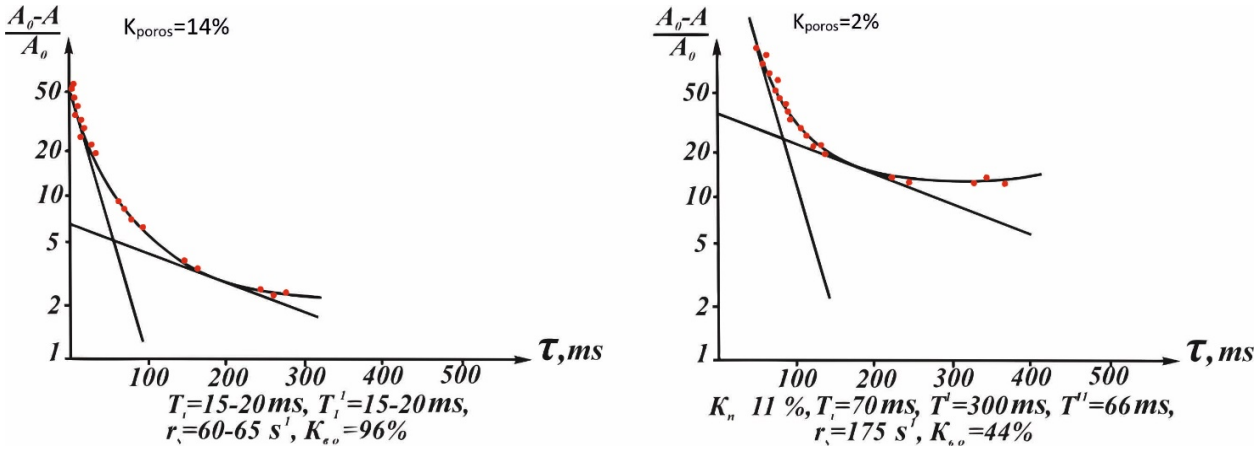

Figure 2 – Relaxation characteristics of the Sarmatian reservoir rocks (the Bilche-Volytska zone of Pre-Carpathian Foredeep) [3 with clarifications]

research from the intervals of Neogene formation of Letnyansky, Hrushivsky and Vyshnyansky gas condensate fields in the conditions of their actual occurrence (Table 2).

Researches, the results of which are presented in table 2, allowed to establish that rocks whose porosity is from 10.3% to 23.2% are characterized by a two-component characteristic (Fig. 2) and, accordingly, different values of longitudinal and transverse relaxation time (T_1 = 300 msec, T_2 = 66 msec, T_1 = 641 msec and T_2 = 63 msec). The permeability coefficient of the rock is almost the same (K_{perm} = $4.8 \cdot 10^{-15}$ mcm^2 and $3.7 \cdot 10^{-15}$ mcm^2). This testifies to its uniform matrix structure and insignificant value of fracturing and cavernous coefficients.

Comparison of the porosity coefficients determined by the nuclear magnetic resonance method with the porosity coefficient obtained by the results of the Preobrazhensky method showed a fairly close relationship, which is characterized by a regression coefficient of 0.94. The obtained results also confirmed the high resolution and efficiency of NMR during operative determination of porosity and oil and gas saturation coefficients of reservoir rocks. In this regard, the use of nuclear magnetic resonance while complex geophysical research optimizes the ability to obtain reliable

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information in the determination of reservoir rocks during the research of complex lithological-stratigraphic strata, as well as provide expressive measurements of physical and petrophysical parameters of rocks at the hydrocarbon searches stage.

Taken into account the complex geological structure of exploration areas and deposits of the Bilche-Volytska zone of Pre-Carpathian Foredeep, it is necessary to strengthen the use of a typical logging complex with the latest gamma-spectrometric methodologies in addition to nuclear magnetic research. This must be done both in the process of logging and during laboratory researches while experimental determinations of petrophysical parameters. It should be noted that the results of gamma logging obtained during researches of Neogene sediments by a typical set of logging methods do not always give an unambiguous description of the type of rock, its mineralogical composition, effective thickness and clay content. The lack of reliable data makes it difficult to identify clayey, sandy, siltstone rocks, which leads to the omission of productive hydrocarbon-saturated strata.

This ambiguity is caused by the complex structure of the rock matrix, the type of cement, as well as the resolution of the hardware of the geophysical method. In order to determine the mineralogical composition of the above mentioned rocks of the Neogene system, as well as to assess their impact on measurement results in particular by radioactive methods, we performed petrographic researches of the reservoir rocks matrix with the aim to determine their type of cement, the coefficients of clay content and residual water saturation. The results of clayey material researches showed that the dominant components in the cement of the rock are potassium-containing minerals, in particular: muscovite, hydromica, glauconite, montmorelonite, and kaolinite. However, in each case the presence and percentage of the above mentioned minerals is different and is associated not only with the type of clayey material. Gamma-spectrometric surveus of clays, sandstones and siltstones for the content of radioactive isotopes of uranium, thorium and potassium were performed on samples taken from the rocks of the Sarmatian, Baden and Helvetic ages. These researches have shown that in most rocks there is a polymineral matrix in which there are radioactive elements and minerals of the sulfides and silicates class. The obtained results of core researches allowed to establish the average content of radioactive isotopes of uranium, thorium, potassium in rocks, which in some cases (table 3) cause a significant increase in the intensity of the radioactive field (ΔJy) while gamma logging. The allocation of sandy and siltstone rocks saturated with hydrocarbons is significantly complicated by the ambiguity of the gamma-logging interpretation in this case.

Table 3 – Average values of radioactive isotopes of Neogene sediments of the Bilche-Volytska zone

No	Age	The content of radioactive isotopes, %		
		$U(Ra)\cdot10^{-4}$	$Th\cdot10^{-4}$	K
1	Helvetic	3,7	6,2	1,8
2	Baden	4,8	9,1	2,2
3	Sarmatian	5,8	7,6	2,3

Gamma-spectrometric analysis of the core material of the Sarmatian and Helvetic ages also revealed that the uneven distribution of uranium, thorium and potassium-40 is mainly characteristic of the Lower Dashav subformation deposits and is observed in most cases in the ND-9, ND-10, ND-11 and ND-12 horizons.

The constructed histograms of the distribution of the concentrations of radioactive isotopes in the rocks (Fig. 3) that fill the cross-section of the Lower Dashav subformation clearly define the differences in the content of radioactive isotopes of uranium, thorium, and potassium. The different percentage of the above mentioned isotopes is caused by the conditions of lithological units' formation, the depth of occurrence and the different structure of the rock. The most different indications of the content of radioactive isotopes U, Th, K40 in the rocks are characteristic of the sediments of the ND-12 and ND-15 horizons.

Conclusion

Based on this, it is possible to use the results of gamma spectrometric surveys for lithology differentiation of exploration areas, assessment of clay and sand content of promising oil and gas saturated rocks.

Summarizing the results of logging and laboratory researches of rocks using the latest technologies, including nuclear magnetic resonance and gamma spectrometry, it can be stated that the including of the above mentioned methods in a set of geological and geophysical surveys will reliably identify oil and gas saturated rocks, evaluate their reservoir parameters within complex lithologic-stratigraphical strata.

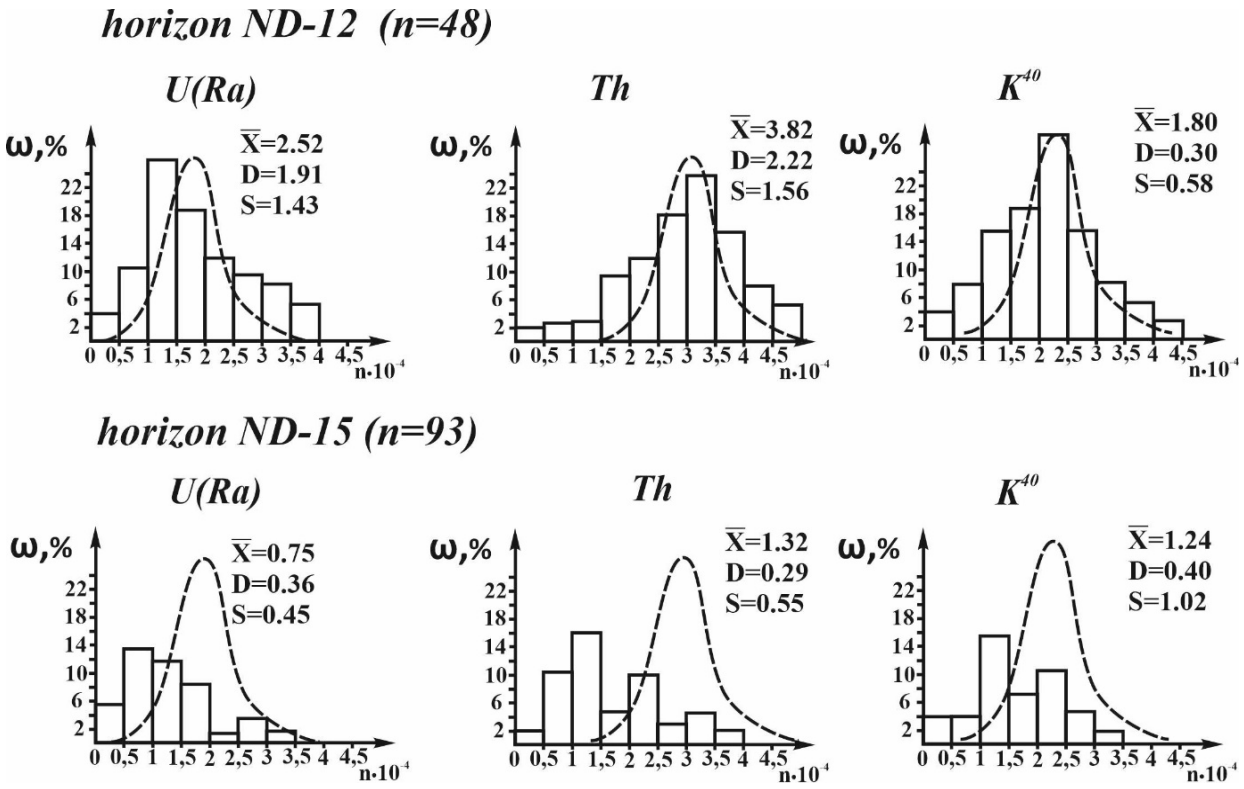

Figure 3 – Histogram of the radioactive isotopes U, Th, K40 distribution in the Sarmatian deposits of the Bilche-Volytska zone of the Pre-Carpathian Foredeep {3 with additions} [3 with clarifications]

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