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NMR LOGGING IN CARBONATE SECTIONS OF AN OIL FIELD WELL

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Carbonates (limestones, dolomites) are complex, heterogeneous reservoirs, where traditional logging methods (gamma-ray logging, neutron logging, litho-density logging and acoustics) often poorly determine porosity and, especially, permeability. In these conditions, downhole nuclear magnetic resonance has become a key method for studying fluid saturation and reservoir properties.

The article presents the results of research on the use of nuclear magnetic resonance in a well (NMR logging) to assess the reservoir properties of carbonate rocks of various textural and structural organization. The features of the formation of T_2 relaxation signals under conditions of multimodal porosity inherent in carbonate reservoirs, including matrix micropores, intercrystalline pores, cavities, and cracks, are considered.

The analysis of the influence of mineralogy, surface relaxation, and diffusion processes on the shape of T_2 spectra and the determination of fluid mobility parameters is carried out. Based on the comparison of NMR logging data with the results of laboratory core studies and other methods of geophysical well study, the limitations of traditional T_2 thresholds and empirical permeability models (Timur-Coates, SDR) in the interpretation of carbonate sections are shown. Improved approaches to the isolation of free and bound fluids are proposed, including adaptive T_2 thresholds and combined interpretation schemes.

The results obtained demonstrate the high potential of NMR logging to improve the accuracy of porosity, fluid mobility, and permeability estimates, as well as to identify productive intervals in complex carbonate reservoirs.

KEYWORDS: NMR-logging; T_2-distribution; porosity; permeability; differential spectrum; NMRes; carbonate rocks; gas saturation; free fluid; bound water.

NMR-КАРОТАЖ В КАРБОНАТНЫХ РАЗРЕЗАХ СКВАЖИНЫ НЕФТЯНОГО МЕСТОРОЖДЕНИЯ

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Карбонаты (известняки, доломиты) представляют собой сложные, неоднородные коллекторы, где традиционные методы каротажа (ГК, НК, ЛК, акустика) часто плохо определяют пористость и, особенно, проницаемость. В таких условиях ядерно-магнитный резонанс в скважине стал ключевым методом изучения флюидонасыщенности и фильтрационно-ёмкостных свойств.

В статье представлены результаты исследований применения ядерно-магнитного резонанса в скважине (NMR-каротажа) для оценки коллекторских свойств карбонатных пород различной текстурно-структурной организации. Рассмотрены особенности формирования сигналов релаксации T_2 в условиях многомодальной пористости, присущей карбонатным резервуарам, включая микропоры матрикса, интеркристаллические поры, каверны и трещины. Проведён анализ влияния минералогии, поверхностной релаксации и диффузионных процессов на форму T_2-спектров и определение параметров подвижности флюидов.

На основе сопоставления данных NMR-каротажа с результатами лабораторных исследований керна и другими методами геофизического изучения скважин показана ограниченность традиционных порогов T_2 и эмпирических моделей проницаемости (Timur–Coates, *SDR) при интерпретации карбонатных разрезов. Предложены усовершенствованные подходы к выделению свободного и связанного флюида, включая адаптивные T_2-пороги и комбинированные интерпретационные схемы.*

Полученные результаты демонстрируют высокий потенциал NMR-каротажа для повышения точности оценки пористости, подвижности флюидов и проницаемости, а также для выявления продуктивных интервалов в сложнопостроенных карбонатных коллекторах.

КЛЮЧЕВЫЕ СЛОВА: *NMR-каротаж, T2-распределение, пористость, проницаемость, дифференциальный спектр, NMR, карбонатные породы, газонасыщенность, свободный флюид, связанная вода.*

МҰНАЙ КЕН ОРНЫ ҰҢҒЫМАСЫНЫҢ КАРБОНАТТЫ ҚИМАЛАРЫНДА NMR-КАРОТАЖ ЖАСАУ

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Карбонаттар (әк тастар, доломиттер) күрделі, біркелкі емес резервуарлар болып табылады, мұнда дәстүрлі каротаж әдістері (гамма-сәулелік каротаж, нейтрондық каротаж, лито-тығыздығы каротажжәне акустика) кеуектілікті және әсіресе өткізгіштігін нашар анықтайды. Мұндай жағдайларда ұңғыманың ядролық магниттік резонансы сұйықтықтың қанықтылығы мен қабат қасиеттерін зерттеудің негізгі әдісі болды.

Мақалада әртүрлі текстуралық-құрылымдық ұйымдардың карбонатты тау жыныстарының коллекторлық қасиеттерін бағалау үшін ұңғымада ядролық-магниттік резонансты (NMR-каротаж) қолдануды зерттеу нәтижелері келтірілген. Карбонатты цистерналарға тән мультимодальды кеуектілік жағдайында, соның ішінде матрицалық микропоралар, интеркристалды кеуектер, каверналар мен жарықтар жағдайында T_2 релаксация сигналдарының пайда болу ерекшеліктері қарастырылады. Минералогияның, беттік релаксацияның және диффузиялық процестердің T_2 спектрлерінің формасына әсерін талдау және сұйықтықтардың қозғалғыштығының параметрлерін анықтау.

NMR-каротаж деректерін негізгі зертханалық зерттеулердің нәтижелерімен және ұңғымаларды геофизикалық зерттеудің басқа әдістерімен салыстыруға сүйене отырып, карбонатты кесінділерді интерпретациялау кезінде дәстүрлі T_2 шектері мен эмпирикалық өткізгіштік модельдерінің (Timur–Coates, SDR) шектеулері көрсетілген. Еркін және байланысты сұйықтықты оқшаулаудың жетілдірілген тәсілдері, соның ішінде адаптивті T_2 шектері және аралас интерпретациялық схемалар ұсынылған.

Алынған нәтижелер кеуектілікті, сұйықтықтың қозғалғыштығын және өткізгіштігін бағалау дәлдігін жақсарту және күрделі карбонатты коллекторлардағы өнімді аралықтарды анықтау үшін NMR каротажының жоғары әлеуетін көрсетеді.

ТҮЙІН СӨЗДЕР: *NMR-каротаж, T2-тарату, кеуектілі, өткізгіштік, дифференциалды спектр, NMR, карбонатты жыныста, газға қаныктылық, еркін сұйықтық, байланысты су.*

Introduction. Nuclear Magnetic Resonance (NMR) logging is one of the most informative methods for studying fluid saturation and Porosity and permeability of formations [1]. Unlike traditional geophysical well logging methods (GWL), NMR does not require calibration based on lithology and is sensitive exclusively to hydrogencontaining pore fluid [2]. This ensures the direct acquisition of transverse relaxation time (T2) distributions, allowing for the quantitative evaluation of bound, capillary-bound, and free water, as well as movable hydrocarbons [3].

Carbonate reservoirs (e.g., limestones, dolomites) remain some of the most complex for petrophysical interpretation [4]. Their porous structure is typically characterized by high heterogeneity: the pore distribution can vary from micropores to macropores, cracks and caverns [5]. These features make traditional geophysical logging methods less effective, especially regarding the accurate assessment of porosity, permeability, and fluid saturation [6].

In carbonate reservoirs, distinguished by complex pore structures and significant lithological diversity, the use of NMR is particularly valuable, as traditional methods often yield ambiguous results. Under these conditions, NMR allows for refining the real effectiveness of the pore space and identifying zones with movable fluids [7].

In this regard, NMR investigation becomes especially valuable because it measures hydrogen content (i.e., fluids) in pores and is relatively independent of rock mineralogy [8]. However, the interpretation of NMR data in carbonate sections faces a number of specific challenges. These include the instability of T2T-2T2 cutoffs, as the classical approach to separating "bound" and "free" water in carbonates can lead to serious errors due to heterogeneous surface relaxivity, complex pore geometry, and internal magnetic field gradients. Theoretical studies have shown that with heterogeneous relaxivity, the direct correspondence between relaxation rate and pore geometry may be violated. Reference [9] shows that surface relaxivity values in pre-salt carbonates correlate strongly with the pore surface-to-volume ratio (S/V), which significantly affects the T2T-2T2 distribution and, consequently, data interpretation.

Work [10] shows that T2T-2T2 distributions obtained via NMR correlate well with mercury injection capillary pressure (MICP) data, allowing for better modeling of carbonate porosity considering various pore regimes (micro-, meso-, macropores).

Considering modern achievements, NMR interpretation technologies such as differential spectra and NMRes analysis can significantly expand analytical capabilities [10]. In this regard, this work, based on deep NMR logging research (Dual-TW mode), fits within the framework of this modern paradigm: it offers not just porosity estimation, but a deeper analysis of fluid saturation structure (bound water, capillary-bound water, free fluid), which is especially important for carbonate reservoirs with gas or hydrocarbons.

Thus, the relevance of the study is confirmed by recent publications and trends in the field of NMR logging of carbonate formations, and our methodological approach (combination of Dual-TW, differential spectrum, and NMRes) can make a significant contribution to improving the accuracy and reliability of the petrophysical model of carbonate reservoirs.

This work interprets NMR logging data from carbonate sections to assess T_2 distributions, porosity, permeability, and fluid types. Results are compared against a standard Triple Combo suite for validation. Additionally, the application of Differential Spectrum and NMRes technologies enabled the identification of gas-saturated zones and provided a more refined mapping of hydrocarbon distribution.

Materials and methods

The object of the study is the carbonate section of an oil field well in the depth interval 2585–2975 m. The section is represented by limestones and dolomites with varying degrees of fracturing and porosity. The upper interval (2585–2775 m) is characterized by a more pronounced content of free fluid and gas-saturated zones, while the lower interval (2775–2975 m) is distinguished by low porosity parameters and an increased share of bound water.

Data from standard geophysical logging (GWL), including density (RHOB), neutron (NPHI), and sonic (DT) logs, as well as laboratory measurements of petrophysical parameters (PHIT, K, Sw) on core samples, were used to verify the results.

Based on available well data, Differential Spectrum Analysis was selected for this study. This method converts echo trains—sequences of bursts followed by the free-induction decay of the magnetic field—into a transverse relaxation time (T2) distribution. From this distribution, the signals for each fluid type within the pore space are sequentially extracted. Because NMR tools primarily investigate the flushed zone, this technology is often integrated with other logging data to provide a comprehensive reservoir model. Additionally, NMRes technology was employed to identify gas-saturated intervals by cross-referencing NMR data with porosity measurements from independent methods [11]

Equipment and Measurement Modes

The studies were conducted using the NMRT-E instrument, which operates on the nuclear magnetic resonance principle (*Figure 1*). Key instrument features:

- Dual-TW mode with echo times of Tw = 2 s and Tw = 8 s, allowing for a wide range of T2T_2T2 relaxation times to be covered.

- The duration of the NMR echo train ensured sufficient signal accumulation at low SNR (3.3–4.7), which is typical for mineralized drilling fluids (≈70 g/L).

- the depth filtering was used to further increase SNR and smooth out random noise.

NMRT-E Specifications presented in *Table 1*.

The Dual-TW mode allows distinguishing fast relaxation components (clay bound water, CBW) and slow components (free fluid, FFI), which is particularly important for carbonate reservoirs with the presence of gas.

Table 1 - **NMRT-E Specifications**

	NMRT-E
Data transmission	WCS
NMRT length	11m
Tool diameter	155 mm
Electronics module diameter	90 mm
Depth of Investigation (Radius)	170 mm
Max Temperature	150°C
Max Pressure	120 MPa

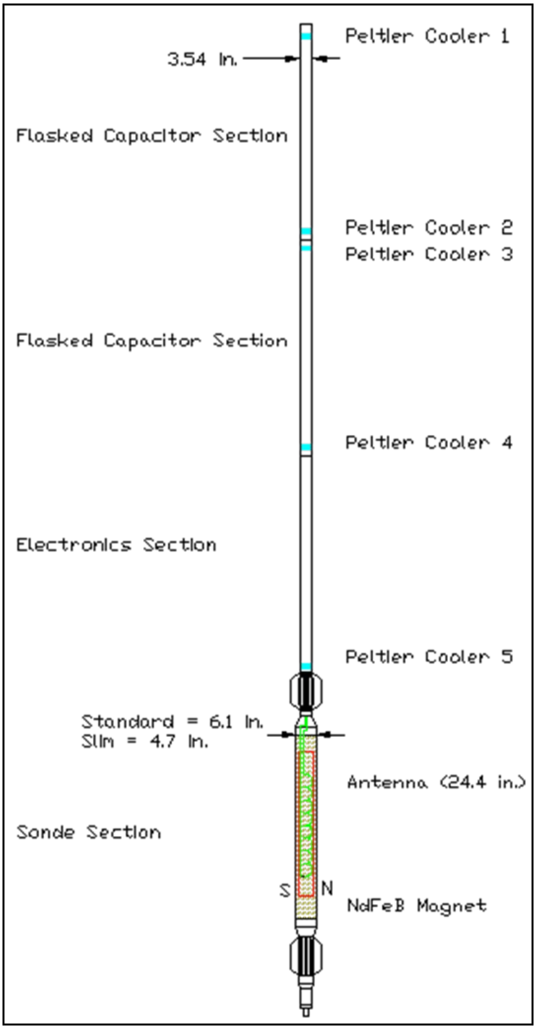

Figure 1 - **Diagram of the NMRT tool**

Data Processing Methods

Echo train filtering using noise suppression and drift correction methods: application of the differential spectrum method to isolate separate water and hydrocarbon components, recognition of capillary-bound water (BVI), free fluid (FFI), and bound water (CBW) based on the position and width of T2T_2T2 peaks.

Data validation and correction: to increase reliability, NMR data were corrected considering the influence of mineralized drilling mud and gas saturation; NMR interpretation results were compared with classical logging methods and laboratory data, which allowed assessing the accuracy of isolating CBW, BVI, and FFI components.

Results and discussion

Due to the sufficiently high salinity of the drilling mud (about 70 g/L), the data contains higher level noise than under optimal conditions. The recorded echo trains have a signal-to-noise ratio (SNR) on the order of 3.3-4.7, i.e., this ratio approaches the lower threshold but is still at an acceptable level (>2) [12]. With such SNR values, it is possible to obtain qualitative porosity and permeability data. Depth filtering was performed, allowing the SNR value to be increased to 5. This technology averages echo trains over the number of depth levels set in the Depth window.

Analysis of Interpretation Results. The distribution of relaxation time T2, porosity calculation, and fluid classification were performed interval-by-interval. Two intervals were highlighted for analysis:

1) Interval 2585-2775 m
2) Interval 2775-2975 m

The NMR analysis included:

Checking the T2 arrival time for various fluid components.

Analysis of porosities calculated via T2 and identification of hydrocarbons using Differential Spectrum Technique.

Attempted identification of light hydrocarbons (gas) using NMRes technology (using porosity from the standard logging suite).

A typical T2 distribution for this interval is shown in *Figure 2*. A clear separation is visible between clay bound water, capillary bound water, and free fluid. On the T2 distribution graph at Tw = 8 s, clay bound water (CBW) is highlighted by a peak at 2.2 ms, capillary bound water (BVI) by a peak at 25 ms, and free fluid (FFI) by a peak at 342 ms, much higher than expected according to the theoretical expectations.

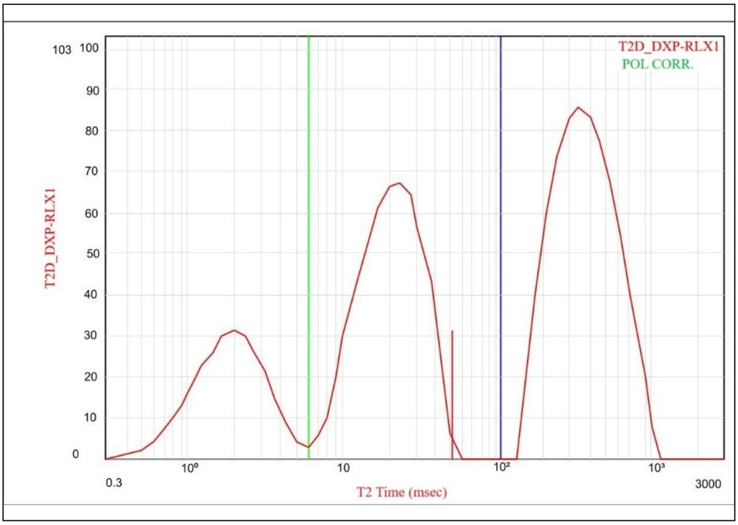

Figure 2 - **T2 Distribution, Tw = 8 s at depth 2697m**

Figure 3 shows the T2 distribution based on Tw 2ms delay data. Only two peaks are distinguished; the first is at 3 ms and the second peak is at 329 ms. It also lags compared to the T2 arrival.

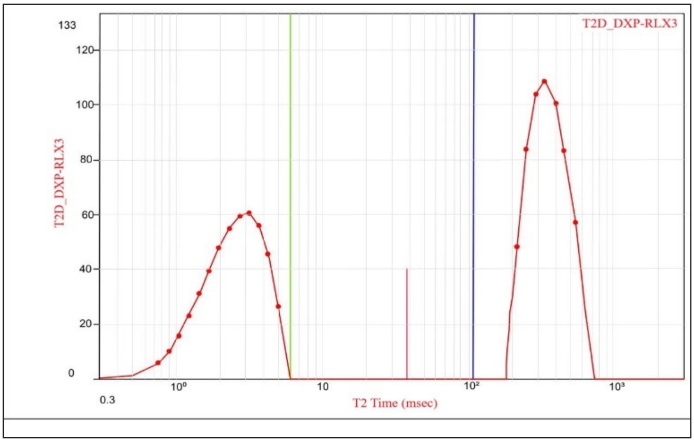

Figure 3 - **T2 Distribution, Tw = 2 s at depth 2697m (SPP3)**

Analysis of Differential T2 Spectra

Figure 4 presents an example of a plot with NMR results in the interval 2585.0-2775.0 m.

The last track shows fluid volumes calculated by NMR T2 (CBW, BVI, FFI) and PHIT-CPX porosity for comparison. PHIT-CPX generally coincides with PHIT-NMR with the exception of gas-saturated areas, which cannot be directly determined from NMR since gas affects NMR porosity by reducing it due to a low Hydrogen Index (HI).

In the interval 2585.0-2775.0 m, a sufficiently good match of porosities NMR T2_PHIT and PHIT-CPX is observed, with the exception of zones with the presence of gas. The mismatch may also be caused by the lithology effect, but this must be studied involving core data. Throughout the interval, a small amount of bound water (CBW) is observed, however, the presence of CBW is observed in the interval 2585.0-2620.0 m, which is also reflected in the CPX analysis. This same section is also noted as a zone of increased cavernousness (washouts); thus, the gas shading reflects not the presence of gas, but the influence of poor borehole conditions on the total PHIT porosity.

For direct determination of hydrocarbons, the Differential Spectrum technology was applied [12]. Initially, dual TW was applied to separate the spectra from one another and highlight peaks corresponding to hydrocarbons and water/filtrate. It is assumed that all additional porosity is filled with gas. Direct presence of hydrocarbons is visible in this interval.

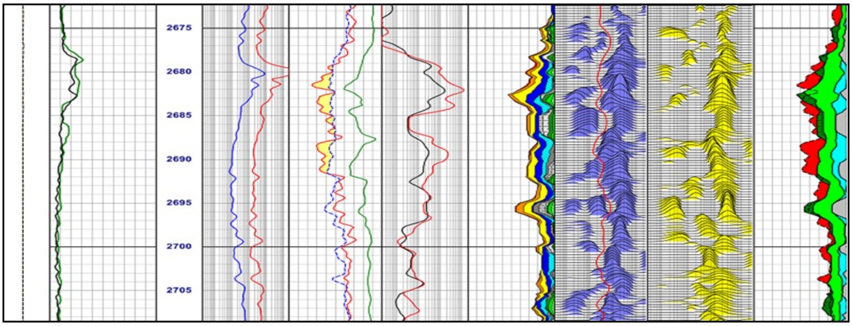

Figure 4 - **NMR Results in the upper interval**

Interval 2775-2975 m

According to the results of the standard logging suite analysis (GR/Resistivity/Den/Neu/PEF) and mud logging data, this interval is represented by carbonate rocks, limestone, and dolomite. According to standard logging data, thick reservoir zones saturated with hydrocarbons are identified.

According to NMR analysis in these intervals, several zones filled with movable fluids (gas, hydrocarbons, free water) are identified [13].

Figure 5 shows a typical T2 distribution for this interval. A clear separation is visible between clay bound water, capillary bound water, and free fluid. On the T2 distribution graph at Tw = 8 s, clay bound water (CBW) is highlighted by a peak at 2 ms, capillary bound water (BVI) by a peak at 26 ms, and free fluid (FFI) by a peak at 243 ms; values correspond to the NMR work planner.

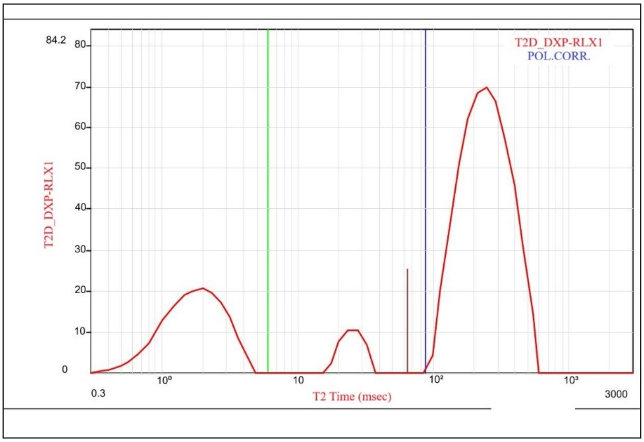

Figure 5 - **T2 Distribution at Tw = 8 s at depth 2821.0m (SPP1)**

Figure 6 shows the T2 distribution for Tw = 2 s. 3 peaks are visible with the following arrival times: CBW 1 ms, BVI 7.4 ms (earlier than expected during planning), and FFI 224 ms (almost coincides with the planner).

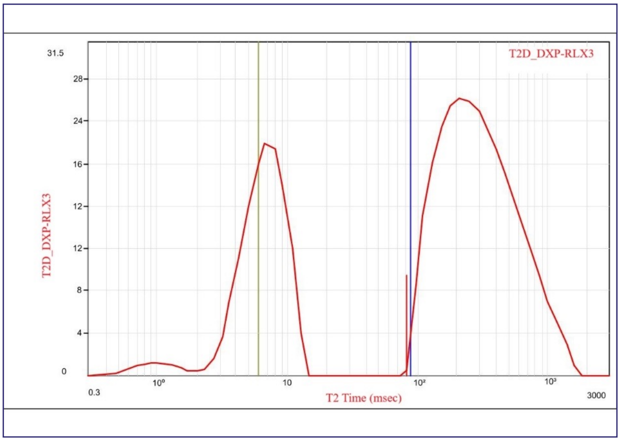

Figure 6 - **T2 Distribution for Tw = 2 s at depth 2821.0m (SPP3)**

T2 data at both delays confirm that we have carbonate rocks in accordance with the planned ones, as well as a large amount of free fluid, which is confirmed by the late arrival time. Regarding porosities, this interval is characterized by very low porosity values; this is also confirmed by CPX analysis.

Differential T2 Spectrum Analysis Technology

Figure 7 presents an example of a plot with NMR results in the interval 2775-2975 m. The last track shows fluid volumes calculated by NMR T2 (CBW, BVI, FFI) and PHIT-CPX porosity for comparison. PHIT-CPX generally coincides with PHIT-NMR with the exception of gas-saturated areas, which cannot be directly determined from NMR as gas affects NMR porosity by reducing it due to low HI. Regarding porosity, the porosity values are very low, which is also confirmed by calculations from the standard logging suite.

In the interval 2775.0-2975.0 m, a sufficiently good match of NMR T2_PHIT and PHIT-CPX porosities is observed, with the exception of several zones with the presence of gas. The mismatch may also be caused by the lithology effect, but this must be studied involving core data. Throughout the interval, a small amount of bound water (CBW) is observed, however, an increase in CBW is observed from a depth of 2860 m to the bottom of the well, which is also reflected in the CPX analysis.

For direct determination of hydrocarbons, the Differential Spectrum technology was applied. Initially, two TW delays were applied to separate the spectra from one another and highlight peaks corresponding to hydrocarbons and water/filtrate. It is assumed that all additional porosity is filled with gas. Direct presence of hydrocarbons is visible in this interval.

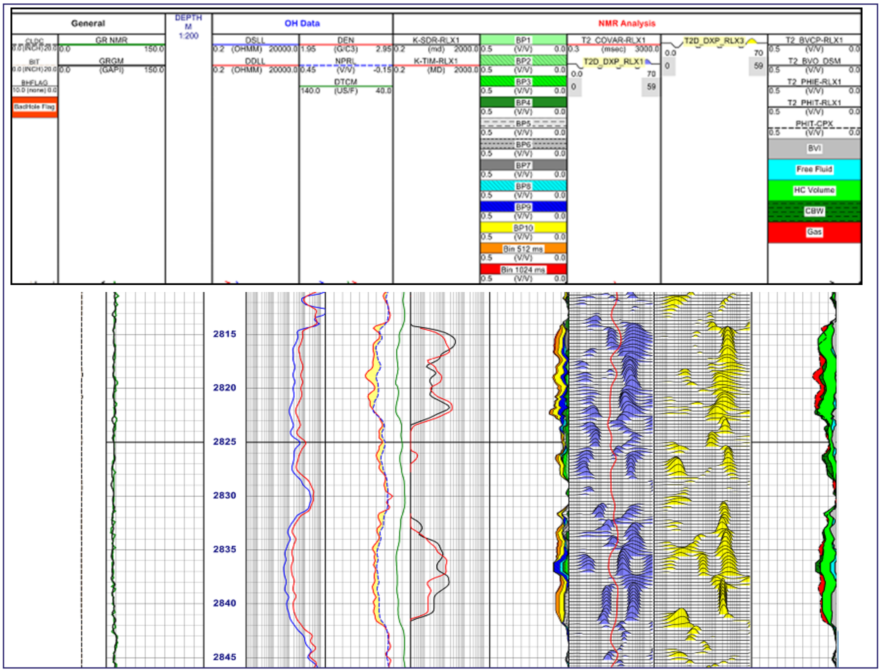

Figure 7- **NMR Results in the lower interval**

Conclusions

NMR logging data are of high quality and suitable for interpretation. The obtained T2 distributions clearly distinguish CBW, BVI, and FFI components. PHIT-NMR porosities agree well with PHIT-CPX. Gas-saturated intervals are confidently identified using NMRes technology. The Differential Spectrum ensures direct isolation of hydrocarbons.

1. The interval 2585–2775 m is characterized by increased fluid mobility.
2. The interval 2775–2975 m has low porosities and an increase in CBW towards the bottom.

The integration of NMR and the standard logging suite increases the reliability of interpretation. The obtained data can be used to refine the reservoir property model. The tabulated results allow for further petrophysical analysis.

The analysis performed demonstrates that the application of nuclear magnetic resonance in the well is one of the most informative and reliable methods for evaluating the reservoir properties of carbonate reservoirs. For carbonate rocks, distinguished by high heterogeneity, complex pore structure, and a wide range of void space types, traditional well logging methods often prove insufficiently sensitive [13]. Under these conditions, NMR logging provides a unique opportunity for direct assessment of pore size distribution, fluid mobility, and the nature of fluid saturation.

Studies have shown that the multimodal structure of the pore space (matrix micropores, intercrystalline pores, vugs, fractures) forms complex T2 spectra sensitive to mineralogy and relaxation mechanisms. It has been established that standard T2 cutoffs and widely used empirical permeability models (Timur–Coates, SDR) have limited applicability in carbonate sections, which can lead to underestimation or overestimation of filtration properties. Based on the comparison of NMR logging data with laboratory core studies, the necessity of an adaptive approach is justified, including the use of modified T2 cutoffs and combined interpretation schemes that consider the features of a specific type of reservoir.

It is shown that the integration of NMR data with traditional geophysical survey methods allows for significantly increasing the accuracy of porosity and fluid mobility estimation, more reliably forecasting permeability, and more confidently identifying productive intervals. The presented results confirm the high potential of NMR logging as a key instrument for studying complex, heterogeneous carbonate systems and optimizing geological-technical decisions at fields of this type.

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