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Possibilities of lithological and stratigraphic division of geological sections based on natural gamma ray spectrometry

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Abstract. Establishing the geological structure of complex sedimentary sections in oil- and gas-bearing areas of Ukraine, specifically their lithological and stratigraphic division, is quite challenging and often ambiguous when interpreting the sequence of sedimentary rock layers. The aim of the work was to study the possibility of lithological and stratigraphic division of a geological section based on the results of natural gamma-ray spectrometry in the interval of the boundaries between the Tournaisian and Visean deposits within the Plyskiv-Lysohorskyi outcrop of the crystalline basement of the Dnipro-Donets Basin. The methodology for studying the boundaries between the Tournaisian and Visean deposits was based on the results of the distribution of the concentration of radioactive isotopes of natural gamma radiation obtained directly during the drilling of exploration and prospecting wells. In addition, core material was taken from the Visean and Tournaisian stages of the Lower Carboniferous coal deposits, and its lithological and petrographic study was carried out by macroscopic description of core samples, preparation and description of thin sections, as well as X-ray structural and gamma-spectrometric analyses of the material composition of the sample collection. In general, the quantitative presence of natural radioactive elements was determined. Based on the results of these comprehensive geological and geophysical studies, it was established that the distribution of natural radioactive elements in the intervals of deposit occurrence depends on the lithological composition of the rocks and, accordingly, changes in the conditions of the sedimentation, which causes changes in the distribution of radioactive elements. Therefore, this particular feature of the structure can be used to trace the boundaries of lithotype distribution in horizons of different stratigraphic thicknesses. Considering that the radioactivity of polymictic rocks was characterised by a significant cumulative effect, and was caused by the increased radioactivity of the rock matrix skeleton and the clay material that fills the intergranular space. Therefore, it is advisable to determine clay content using gamma-ray spectrometry results based on the concentration of potassium-40 or gamma logging data. The introduction of such approaches not only facilitates the identification of boundaries between deposits but also enables the reconstruction of the physical and geological conditions under which the sedimentation of different lithotypes of rock was deposited

Keywords: lithotypes; reservoir; spectrometry; geological boundary; sedimentation

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Introduction

The decline in hydrocarbon production from geological sections of exploration and appraisal structures was affected by both objective and subjective factors. One of these objective factors is the polymictic structure of terrigenous deposits in oil- and gas-bearing formations. Additionally, the reservoir rock matrix has a significant impact on the results of geophysical well logging (GWL). The study of such complex reservoir rocks using a standard GWL is difficult in some cases, particularly during the interpretation of gamma-ray logging (GR) and neutron methods. In most cases, when core material is available, the concentration of uranium, radium, thorium and potassium in rock is traditionally determined by chemical methods in laboratory conditions and usually in small volumes. Since chemical methods are labour-intensive and require significant costs and large amounts of chemical reagents, there is a need for alternative methods.

In particular, geophysical methods were proposed for determining radioactive elements in rock matrices, which allow for high-speed and unambiguous detection of radioactive elements, particularly uranium, thorium and potassium, in wells. In addition, spectrometry methods will allow the composition of complex structures to be determined in a lithological-stratigraphic section, and clayey and carbonate layers to be identified in intervals of polymictic coal deposits, followed by the selection of core material. Such studies contribute to the discovery of additional promising hydrocarbon accumulation sites within the Visean and Tournaisian deposits, which will make it possible to increase their reserves. In the process of oil exploration and development in the Dzhunhar basin, it was proposed to use natural gamma-ray spectral logging to assess reservoir productivity. It was the method of lithological identification of gamma-ray spectrometry that allowed for an increase in the accuracy of the distribution of formations along the geological section, to conduct an accurate interpretation of the formation lithology, and to assess the composition of the sedimentary environment.

The work of B. Shen *et al*. (2021) showed the possibility of using elemental logging in wells on the western edge of the Ordos Basin in the Changqing oil field and proved the presence of radioactive elements uranium, thorium, and potassium. The analysis of the principles of natural gamma ray and elemental logging measurement was performed to establish reference approaches for the separation of formations during drilling and to determine the formation lithology itself. In the article by W. Li *et al*. (2022), an approach was proposed for establishing the boundaries of sand reservoirs based on a created petrophysical distribution model with facies control. The model was created based on the volume of the sand body to identify excessively large sand bodies. This method allows to create a more realistic three-dimensional geological model of beach shoal sands in coastal areas. Their result shows that the property models better reflect the characteristics of the petrophysical distribution of the horizons only. A slightly different approach to lithology and reservoir identification was used by L. Xia *et al*. (2021), where a quantitative method was used to compare and distinguish a section with complex lithology in the Bohai Sea exploration area. The proposed method can realise the quantitative identification of reservoir lithology and effectively eliminate the deviations caused by many factors in lithology identification, thereby ensuring the accuracy of the separation of complex lithology sections.

The article by W. Wu *et al*. (2023) investigated the influence of Milankovitch cycles on sedimentation in fine-grained deep-water rocks of the lower Es3 subdivision of the FY1 well in the Dongying Basin (China). The authors identified stratigraphic cyclicity associated with precession and eccentricity using spectral analysis of geochemical and logging data. It was established that warm and humid climatic phases favoured the accumulation of organic matter, forming promising intervals for shale oil. In the work, the effectiveness of cyclostratigraphy for the accurate identification of productive zones in continental basins was confirmed. In the work of Q. Zhong *et al*. (2024), a reconstruction of the sedimentation process of fine-grained sedimentary rocks was carried out, studies were conducted that provide a benchmark for the classification of facies and characteristics of their distribution, and an assessment of optimal zones for shale oil reservoirs in graben lake basins was performed.

In the process of sedimentation, when sedimentation conditions change, radioactive elements are distributed, which is reflected in the pattern of changes in the mineral composition of rocks, as well as in the physical and geological conditions of their occurrence. The aim of the study was to substantiate and establish the possibility of using gamma spectrometry to assess the nature of the transition zone and trace the boundary between sediments on the example of the Visean and Tournaisian stages. Accordingly, the objective was to evaluate the possibility and informativeness of using natural gamma-ray spectrometry to establish the boundaries of the division between the Visean and Tournaisian deposits within the Plyskiv-Lysohorskyi outcrop of the crystalline basement of the Dnipro-Donetsk Basin axial zone.

Materials and Methods

Considering that the distribution of natural radioactive elements depends on the mineralogical composition of rocks and their physical and geological conditions during sedimentation, a study was conducted on the possibility of using gamma spectrometry to establish the transition zone and boundary between lithotypes using the example of the Visean and Tournaisian stages within the Plyskiv-Lysohorskyi outcrop of the crystalline basement (Fig. 1) of the Dnipro-Donets Basin.

The study of the geological structure and prospects for oil and gas content within the Plyskiv-Lysohorskyi outcrop is inextricably linked to oil and gas exploration in the northwestern part of the Dnipro-Donetsk Basin as a whole (Hrol & Lurie, 2021). The Plyskiv-Lysohorskyi outcrop of the crystalline basement extends along the basin in a long ridge oriented latitudinally, measuring more than 50 km by 20 km (Lukin *et al.*, 2020). Its formation occurred under complex geological conditions, characterised by multidirectional movement of the basement blocks, which significantly influenced the development of the sedimentary complex (Lazaruk, 2012; Lazaruk, 2023). Within the Plyskiv-Lysohorskyi outcrop of the crystalline basement, the supersalt sedimentary complex almost completely inherits the tectonic structure of the crystalline basement. The Sofiika-Yaroshivka uplift zone can be traced here, within which there are separate Vasylivka, Sofiivka, Berezhivka, and Yaroshivka uplifts, and a whole series of small-amplitude closed and semi-closed domes can be distinguished.

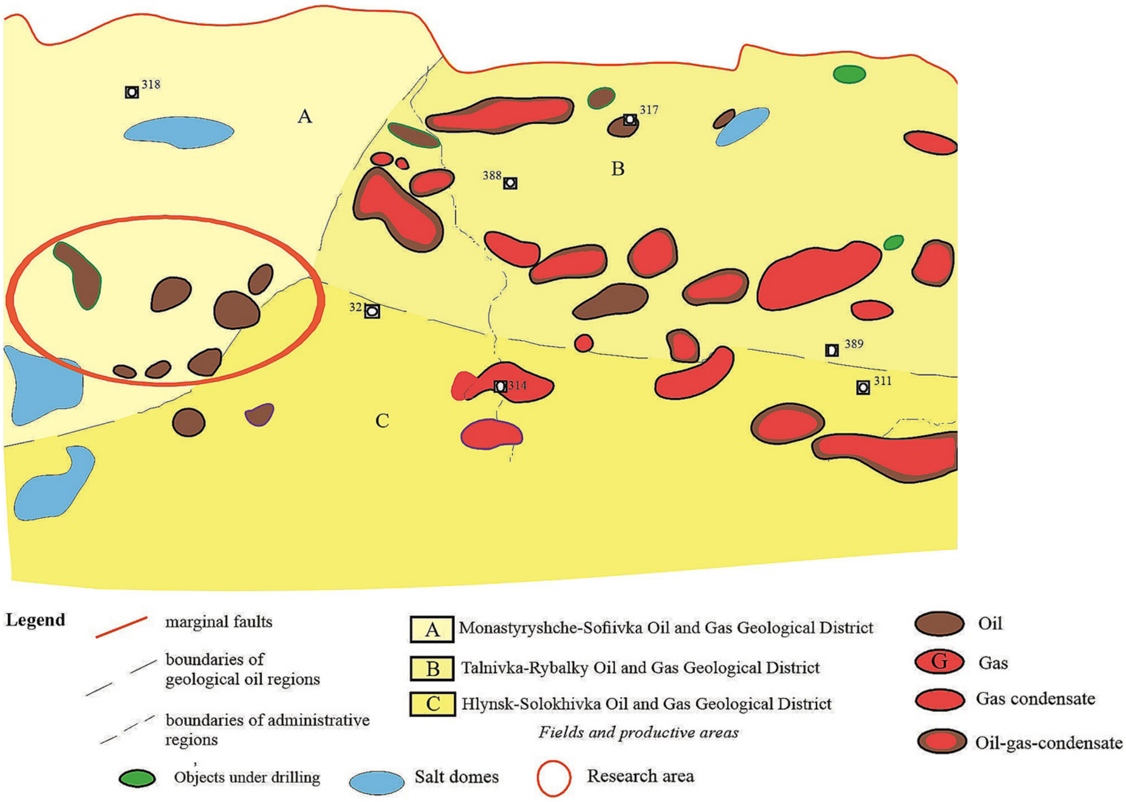

Figure 1. Overview map of the study area

Source: created by the authors with the use of M. Ivaniuta (1998)

To study the lithological and stratigraphic structure of wells drilled within the Plyskiv-Lysohorskyi outcrop of the crystalline basement, core material was taken from the Lower Visean and Tournaisian stages for lithological and petrographic studies, including a macroscopic description of samples, as well as preparation and description of thin sections (Bezrodna & Gozhyk, 2018), X-ray structural analysis of the material composition of the studied lithotypes (Danylchenko *et al.*, 2019), and evaluation of the results of gamma-spectrometric analysis (Vyzhva *et al.*, 2023) for the content of natural radioactive elements. A radiometric device, a spectrometer, was used to record radioactive emissions. It was used to study the spectral characteristics of radioactive radiation and determine the type and concentration of radionuclides (^{40}K, ^{235}U(Ra), ^{232}Th). The procedure for measuring instrumental spectra involves recording the number of pulses n during the exposure time t in the spectrometer channels and further calibration of its energy scale. The exposure time was selected taking into account the permissible pulse frequency error in the corresponding channels. During the interpretation of the obtained spectra, the radiation energy of charged particles and γ-quanta was determined by the position of the total absorption peaks on the energy scale, which is placed along the abscissa axis in accordance with the calibration data. It should be noted that in addition to the main lines of the source under study, secondary peaks may appear in the spectra, which arise as a result of side processes of interaction of radiation with the detector material and its shielding. In such cases, to accurately identify the peaks of total energy absorption, the spectrum under study was compared with the spectra of reference monoenergetic sources with similar energy characteristics (Vyzhva *et al.*, 2020).

To establish the transition zone between lithological rock types, GR and electrical methods were used. The GR method measured the intensity of radioactive radiation of rocks in wells using a γ-radiation indicator. Geiger-Muller counters or more efficient and modern scintillation counters were used as indicators. To determine the boundaries of the formation with an increased radioactive background with acceptable accuracy, we focused on the moment of the rise of the GR curve in the foot and its decline in the roof of the formation boundaries. As for the electrical methods for determining the boundaries of formations and their thicknesses based on the apparent resistivity curves, they are based on the study of the distribution of artificial stationary and quasi-stationary electric fields in rocks. Typically, the resistivity of the environment surrounding a downhole device (probe) is determined by the observed values of the potential U, the potential difference ΔU, or the electric field strength E, created by a current source with a strength of I. To establish a relationship between the resistivity of the medium under study and the measured electric field characteristics (U, ΔU and E), the current strength I, and the geometric dimensions of the downhole probe, it was necessary to determine the potential value in the medium where the point source of current is located (Kurgansky & Tishayev, 2011).

The content of natural radioactive elements K, U(Ra), Th was determined within the collection of selected core material from the intervals of the Visean and Tournaisian deposits and compared with the data of GR and electrical methods. The lithological and petrophysical analysis focuses primarily on studying the lithological characteristics of rocks, as well as the physical and physicochemical processes that produce their physical properties, such as porosity, electrical conductivity, density, elasticity, etc. In addition, the analysis covers petrophysical parameters that describe the participation of rocks in geological and physical and chemical processes permeability, porosity coefficient, specific electrical resistance, elastic wave velocity, and others. In practice, the use of lithological and petrophysical methods makes it possible to divide rocks into strata, series and suites, to correlate simultaneously formed geological formations, and to identify promising areas for oil and gas exploration.

Results and Discussion

According to the results of the description of the thin sections, the lithological varieties of rocks had the following characteristics. Argillites could be divided into marly, red-coloured and chlorite-calcareous types according to the type of cement. The main part of the clayey material consisted of brown illite, sericite and sometimes hydrobiotite. The quartz content was 5-40%, quartzite – 5-20%, and chlorite – 1-3%. Alevrolitic argillite with remains of siliceous organisms was formed in a slightly acidic environment at shallow depths, where no coarse-grained material could reach. Alevrolitic argillite was carbonaceous, contained carbonised remains and was formed in coastal marshes. Monomictic sandstones consisted of well-sorted quartz fragments cemented by kaolinite, with rare calcite inclusions in the pores. This type of sandstone was mainly formed by semi-rounded fragments (75-85%) measuring 0.3-0.6 mm. Quartz predominated (60-63%), with quartzite (1-5%) and siliceous-clayey and sericite-clayey fragmental rock were also present. Fragments of orthoclase, oligoclase, occasionally colourless garnet, biotite and muscovite were noted. Polymict sandstones were mainly fine-grained, yellowish-greenish-grey in colour, and consisted of 80-85% fragmental material. The fragmentary material had the following composition: 25-50% quartz, other fragments were represented by quartzite, feldspar, as well as clayey-siliceous, quartzite-sericite, sericite-chlorite and clayey-sericite rock varieties. In addition, particles of orthoclase, oligoclase, albite, muscovite, biotite and chlorite were found in polymictic sandstones.

Rare were isolated grains of colourless garnet and zircon. Gravelites mainly consisted of fragments ranging in size from 3 to 8 mm (50-59%). The fragmental material was represented by limestones, marls, sandstones, siltstones and shales. Polymict gravelites consisted of fragments of quartz, quartzite, quartzite shale, chlorite argillites, limestones and, occasionally, fragments of effusive rocks. Limestones were grey with a pinkish tinge. The rock consisted mainly of calcite, dolomite, impurities of ferrous carbonate and a small amount of hematite-clay substance. As shown in Table 1, the distribution of radioactive elements in the rock types of the geological section within the Plyskiv-Lysohorskyi outcrop followed a general pattern, ranging from maximum values in argillites to minimum values in limestones, with a gradual change in siltstones and sandstones.

Table 1. Content of natural radioactive elements in the geological section of the Plyskiv-Lysohorskyi outcrop in the central part of the Dnipro-Donets Basin

Lithology	K, %	U(Ra), 10^{-4}%	Th, 10^{-4}%
Argillite	2.6-3.1	5.1-5.7	11.5-14.0
Siltstone	1.6-2.4	4.3-5.7	9.4-12.0
Monomictic sandstone	0.2-0.7	0.2-2.0	2.6-7.0
Polymict sandstone	2.5-2.7	2.7-3.7	5.0-8.6
Gravelite	0.6	1.3	2.1
Polymict gravelite	1.8	2.3	2.6
Siltite argillite	0.5-1.0	2.5-2.7	10.5-11.6
Carbonaceous silty argillite	0.3-0.68	4.7-6.5	16.5-25.7
Sandstone gravelly	0.2-0.4	1.5-1.6	4.5-14.0
Gravelite	0.2	0.7-0.8	5.0-5.6
Limestone	0.4-0.9	3.2-11.0	1.2-5.5

Source: developed by the authors

The content of radioactive elements (^{40}K, $^{235}U(Ra)$, ^{232}Th) did not vary depending on the structure of the geological section of the deposits. However, there was a significant difference between lithological types in terms of radioactive elements. Siltstone and carbonaceous argillites had significantly lower potassium content and higher U(Ra) and Th content compared to flinty argillite, which could be explained by the conditions of sedimentation, in particular, the transition from deep-sea to continental conditions of formation. The content of ^{40}K, $^{235}U(Ra)$, ^{232}Th in siltstones within different deposits of the outcrop had a similar concentration but lower values compared to argillites. In most cases, the radioactivity of sandstones varied depending on the mineralogical composition of the rock matrix and cement of the rock. Polymictic sandstones, due to the presence of feldspars and mica, were characterised by a significantly higher potassium content compared to ordinary sandstones. The content of ^{40}K, $^{235}U(Ra)$, and ^{232}Th in polymictic sandstones at different deposits remained almost unchanged. No significant differences in the content of radioactive elements were observed in gravel sandstones, gravelites and limestones. The only exception was limestones containing carbonaceous matter, which led to an increased content of $^{235}U(Ra)$.

Thus, lithological varieties of different mineralogical composition are distinguished by their content of naturally occurring radioactive elements. Changes in the distribution of radioactive elements ^{40}K, $^{235}U(Ra)$, and ^{232}Th mainly depended on the conditions of sedimentation, which made it possible to determine the transition zone and trace the boundary between stratigraphic horizons. Thus, the analysis and generalisation of lithological-stratigraphic varieties, particularly the aleurite-clayey strata, made it possible to characterise the section as comprising coarse-, medium-, and fine-laminated rocks with weakly developed rhythmicity, complicated by variable proportions of lithological types and the emergence of additional layers. It should be emphasised that these layers slightly disrupted the overall uniformity of the thickness; however, they did not constitute reference horizons (benchmarks) within the articulation zone of the identified strata.

In the examined lithological and stratigraphic section, no distinct boundary was identified between the Tournaisian and Visean strata (in particular, well-preserved basal conglomerates and other reference horizons, including angular unconformities). Consequently, the presence of various types of argillites made it difficult to visually subdivide the exposed thickness. In this context, the change in the lithological composition of the section was generally moderate, resulting from variations in the qualitative and quantitative characteristics of the rocks alongside significant changes in microrhythms. This was confirmed by experimental studies conducted on core samples obtained from the Tournaisian, transitional, and Visean rhythmites. The geological parameters obtained indicated small amplitudes of oscillatory movements and the gradual, impulsive development of transgressions and regressions induced by these movements (Iuras *et al.*, 2023). A considerable number of species of Tournaisian fauna were discovered in strata attributed to the Visean age. Given that floristic remains in submerged coastal areas rarely provided a reliable basis for age determination, the relative stability of the terrestrial biocenosis during transgressions facilitated the prolonged dispersion of such plant remains across different rock types (Stryzhak, 2021). This, in turn, further complicated the age determination of sedimentary rocks within thick geological sections of the Visean and Tournaisian deposits.

The upper part of the Tournaisian complex was characterised by several distinct mineralogical features. These included the widespread occurrence of kaolinite across various rock types, the formation of pyrite concretions of differing sizes and volumes, and the presence of rock layers containing siderite, other ferrous carbonates, and occasionally calcite. Lithologically, this interval exhibited a broad range of strata enriched with large carbonaceous plant remains, variegated layers with reddish and brownish hues indicative of oxidising environments typical of continental formations, and medium- to coarse-grained rocks (conglomerates, gravellite-like formations, gravels, and various sandstones) with quartz-kaolinite and quartz-carbonate-kaolinite cements, which defined the reservoir properties of the rocks. Additionally, layers of siliceous argillites and other siliceous formations were only sparsely distributed. These rocks typically exhibited elevated contents of radioactive elements adsorbed onto minerals such as kaolinite, iron hydroxides, and organic matter, as well as those localised in accessory minerals that enriched the weathering crust and its eroded products. Most of these rocks were defined by lenticular, cross-bedded, and coarse-bedded textures, as well as conglomeratic, regenerative structures, and features influencing the volumetric properties of lithotype porosity.

The lower part of the Visean complex was mineralogically distinguished by the widespread occurrence of cryptocrystalline chemogenic silica. This silica enriched various types of argillites, aleurolites, and other rocks, enhancing their strength and reducing porosity. Hydromica (and less commonly, montmorillonite) with elevated potassium content predominated, while kaolinite and kaolinite-bearing rocks played a subordinate role. Finely dispersed pyrite inclusions were common, and certain horizons showed enrichment in minerals such as sphalerite, barite, and chalcedony, suggesting episodic inflows of mineralised thermal waters into the basin. Horizons enriched in calcite were also noted. The aforementioned strata exhibited widespread accumulation of dispersed organic matter, fine carbonaceous detritus, rocks containing siliceous microfauna within silty argillites and siliceous argillites, and the presence of limestones and marls.

Most of the studied rocks were characterised by enrichment in radioactive potassium (^{40}K) and other elements, as well as by thinly laminated textures and conglomeratic, pelitic, and lepidoblastic structures (Selley, 2000). The transitional interval between the Tournaisian and Visean strata comprises interbedded sedimentary formations analogous to the rocks of the corresponding stages. The principal lithological varieties identified in the geological section within the Plyskiv-Lysohorskyi outcrop, where the content of natural radioactive elements was determined, include: argillites; siliceous and carbonaceous argillite-aleurolites; aleurolites; monomictic and polymictic sandstones; gravelly sandstones; gravelites and polymictic gravelites; and limestones (Table 1). The concentrations of natural radioactive elements, such as potassium (K), uranium (U(Ra)), and thorium (Th), were measured using selected core material from both Visean and Tournaisian intervals and correlated with gamma-ray (GR) and electrical logging data.

Well 8. Core samples were taken from the interval 4,115-4,176 m. In the interval 4,130-4,160 m, the highest gamma activity recorded in the well interval was observed, averaging 20 μg/h, with gamma activity in thin interbeds reaching 40 μg/h. According to the results of lithological and petrophysical analysis, the rocks were mainly siltite-argillite. However, in the interval 4,115-4,132 m, siltite-argillite and siltstone with clay-siliceous cement of relatively deepwater origin were observed. In the lower part of the section, the siltite-argillite changes to fine-grained sandstone with organic matter residues. The content of radioactive elements varies within: K – 0.6-1.3%, U(Ra) – (2-3) × 10^{-4}%, Th – (8 - 12) × 10^{-4}%.

Below, in the interval 4,136-4,171 m, argillites and siltstones contained carbonised plant fragments and a significant amount of carbonised algae enriched with small and large crumbs. Accordingly, it could be assumed that they were formed in slightly acidic coastal shallow marsh conditions. The rocks were characterised by a low K content of 0.1-0.5%, an increase in U(Ra) of (10-15) – 10^{-4}%, and Th of (15-30) – 10^{-4}%. In the interval 4,171-4,176 m, colourful siltite-argillite changed into quartz and gravelly sandstones with kaolin-quartz cement. Content of radioactive elements: in variegated argillites: K – 0,1-0,6%, U(Ra) – 3 × 10^{-4}%, Th ~ (10-18) × 10^{-4}%. In sandstones and gravelly sandstones, the content of radioactive isotopes was respectively: K – 0.3%, U(Ra) – 1 × 10^{-4}%, Th – 5 × 10^{-4}%.

According to preliminary results, the boundary of the lithotype boundaries of the Tournaisian and Visean stages was predicted at a depth of 4,148 m. No changes in the recorded parameters were observed in this interval on the GR and SW curves (Fig. 1) or gamma-ray spectrometry. The transition from continental, coastal marsh, relatively shallow sedimentation conditions to deep-sea conditions (Lazaruk, 2022) can be traced by changes in the content of natural radioactive elements, namely, an increase in the content of radioactive potassium and a decrease in the content of U(Ra) and Th (Fig. 2).

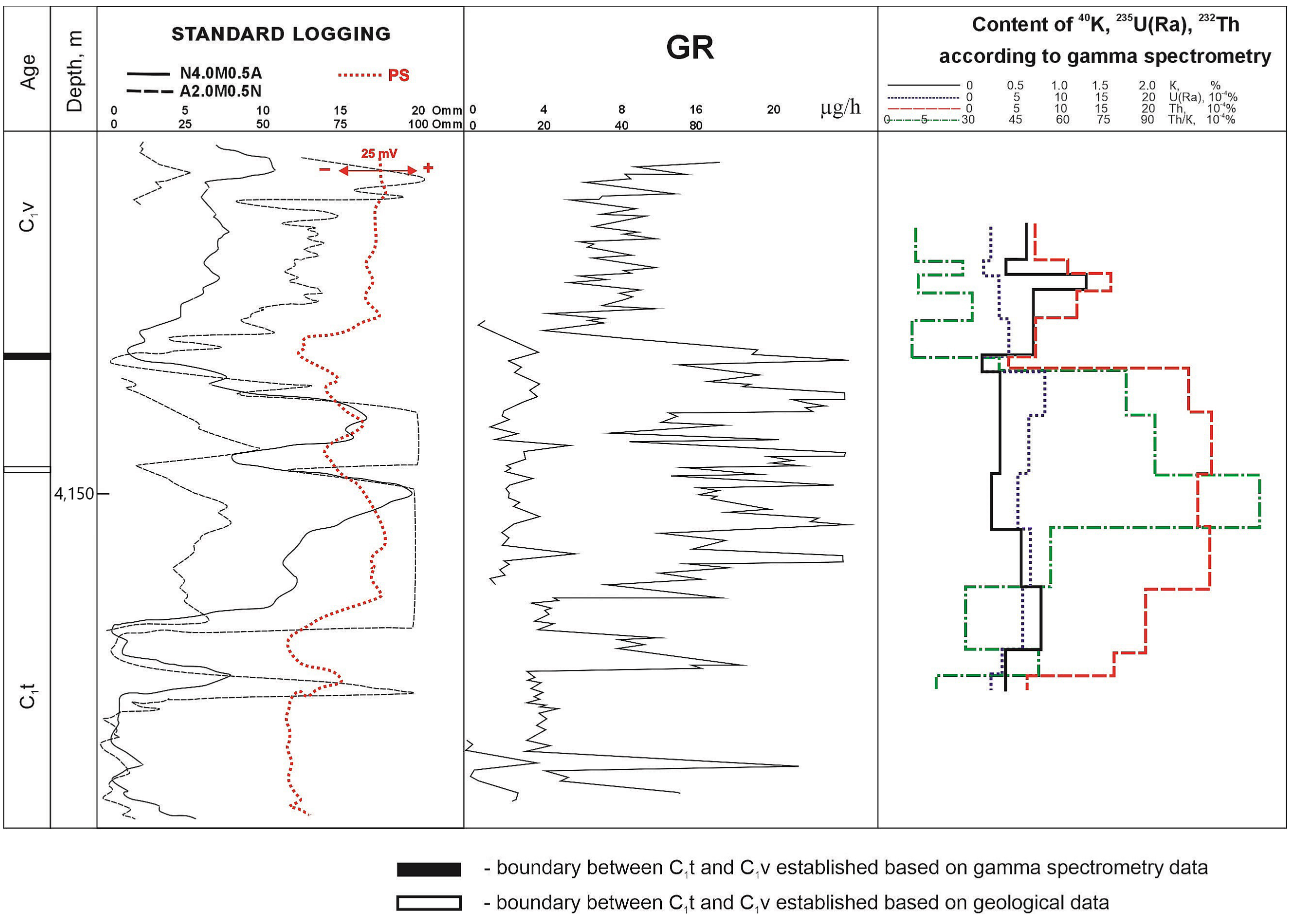

Figure 2. Well 8. The interval of exploration of depths 4,115-4,176 m

Source: made by the authors

The most informative parameter for studies of this type of rock was the relative value of Th/K. A sharp change in the value of this parameter was observed only at a depth of 4,136 m, which could already be attributed to the boundary between the Tournaisian and Visean deposits.

Well 4. The core was taken from the interval 4,041-4,100 m. As in the section of Well 8, the distribution of radioactive elements was caused by changes in the mineralogical composition of rocks and geochemical conditions of sedimentation processes. In the interval of 4,041-4,048 m, the rocks were represented by siltite-argillite with inclusions of isolated detrital fragments. They were characterised by a relatively high K content of (1-1.5)%, a decrease in U(Ra) of (2-4) to 10^{-4}%, and an increased content of siltstone containing carbon-emitting residues of various sizes, as well as small layers of carbonaceous siliceous argillite. The content of radioactive potassium decreased to 0.2-0.5%, U(Ra) and Th increased to (6-9) × 10^{-4}% and (27-30) × 10^{-4}%, respectively. Accordingly, these rocks were replaced by fine-grained sandstone with quartz kaolinite cement and small carbonised fragments with depth. The average content of radioactive potassium in the section was 0.2%, U(Ra) – 8 × 10^{-4}%, and Th – 30 × 10^{-4}%. In the interval 4,062-4,069 m, there was a multi-grained sandstone and gravel with quartz-alumina cement. The content of U(Ra) decreased sharply to 1.5 × 10^{-4}% and Th – 6 × 10^{-4}%.

At depths ranging from 4,069 m to 4,100 m, the sedimentation process was repeated. The upper interval of the lithological and stratigraphic section was represented by siltite-argillite with organic residues, while below it, there were colourful siltite-argillite, which sometimes contained hydrohematite impurities. Below the section, there are argillites, sometimes sandy siliceous, which turned into siltstone with quartz-clay cement enriched with scattered organic matter. These rocks were underlain by medium-grained and gravelly sandstone with kaolin-quartz cement and sulfide-quartz-barite cement. Accordingly, the content of radioactive elements in the above lithotypes was also changed. Thus, in the transition zone, there was a rhythmic nature of sedimentation processes. The transition from continental, coastal shallow-water sedimentation conditions to marine conditions was marked by an increase in the content of radioactive potassium, a sharp change in the Th/K ratio, which could be taken as the boundary of the transition from the Tournaisian to the Visean deposits (Fig. 3).

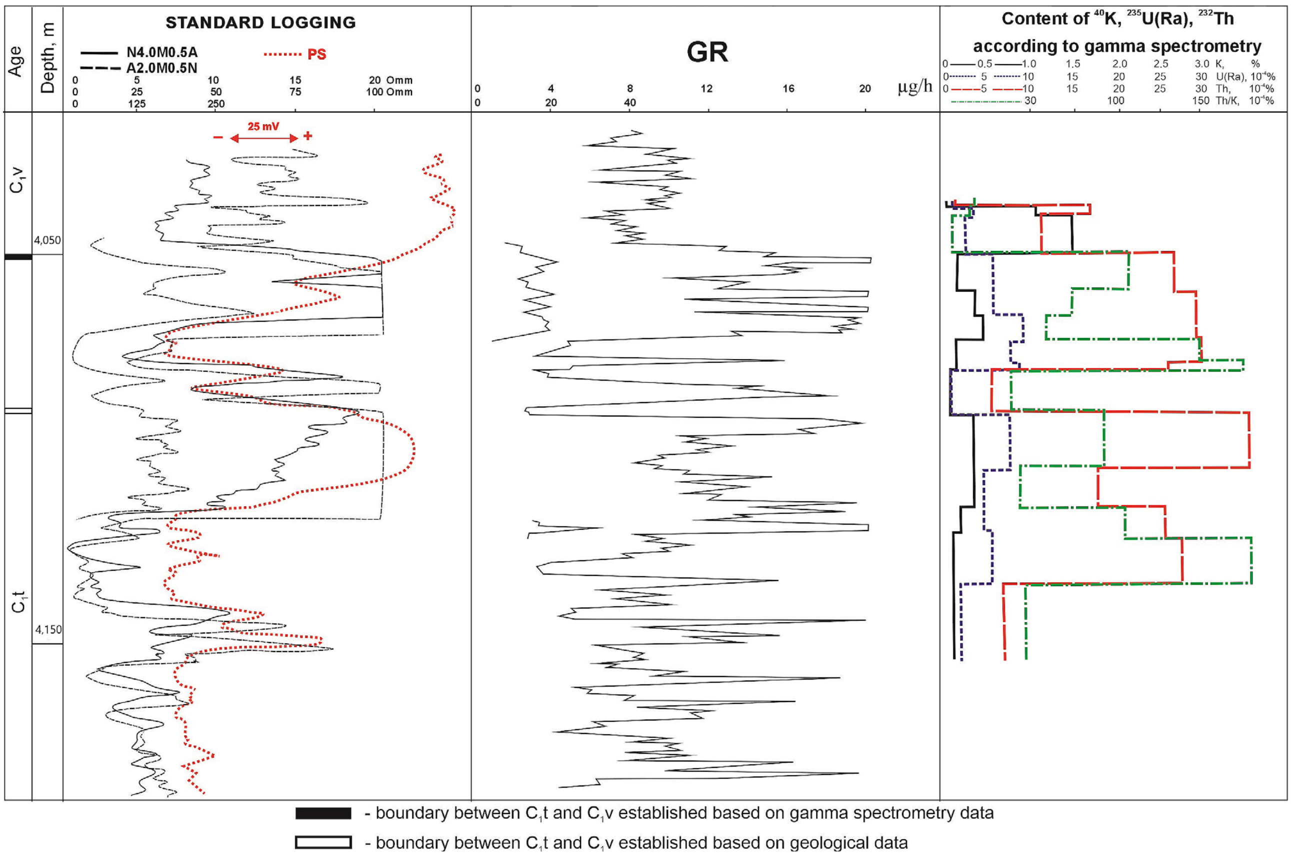

Figure 3. Well 4. The interval of exploration of depths 4,041-4,100 m

Source: made by the authors

Well 3. At depths of 4,759-4,767 m, the lithological and stratigraphic section consisted of siltite argillite with separate inclusions of carbonaceous material. Below, in the interval (4,767-4,770) m, there was silty-carbonaceous argillite with layers of limestone. The rock was characterised by average radioactivity values: K – 0.6-0.7%, U(Ra) –

(4-6) × 10^{-4}%, Th – (5-16) × 10^{-4}%. At depths of 4,919-4,936 m, the rock was represented by gravelly sandstones and gravelites with clayey-quartz kaolinite cement. They were characterised by a sharp decrease in potassium content – to (0.1-0.2)% and U(Ra) to 0.5 × 10^{-4}%, with an average thorium content of 9 × 10^{-4}% (Fig. 4). The change in lithological composition from coarse-grained gravelly sandstones to silty-clayey rocks with carbonaceous inclusions characterises the transitional thickness from Tournaisian to Visean deposits. The boundary between these layers was identified at a depth of 4,765 m and confirmed by a change in sedimentation conditions from marine and coastal to continental, which in turn was reflected in the distribution and abundance of natural radioactive elements.

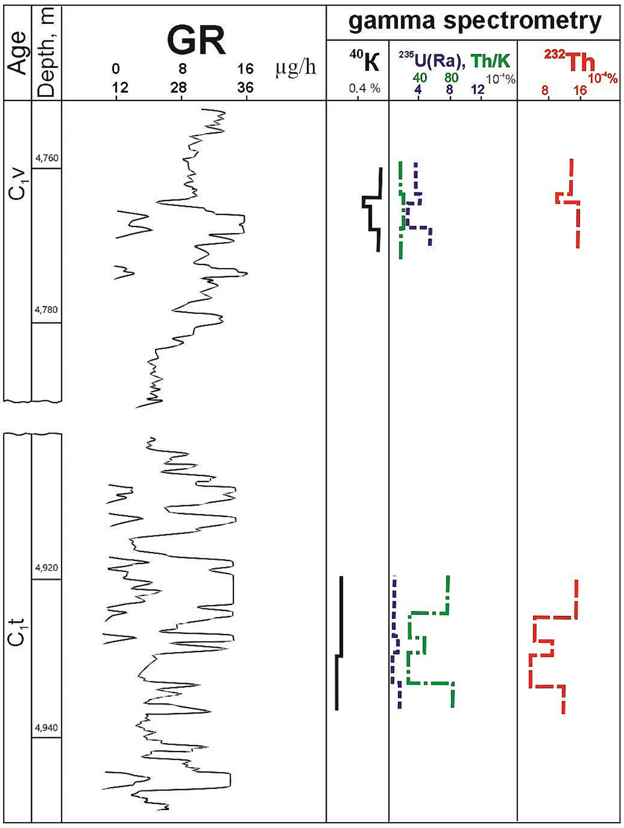

Figure 4. Well 3. The interval of exploration of depths 4,759-4,767 m

Source: made by the authors

Well 1. The rocks in the depth interval of 4,153-4,190 m were studied, with comparison of the results of the GR curve data and the distribution curves of K, U(Ra) and Th (Fig. 5). Comparing the radioactive parameter data, it was observed that the increased values of the GC method were characteristic of rocks in the depth interval of 4,117-4,212 m. No core was taken in the depth interval of 4,117-4,153 m. Starting from a depth of 4,153 m and down to 4,179 m, the rocks were represented by siltstone with some thin sandstone layers. These rocks were formed under marsh facies conditions, where the accumulation of organic matter sharply decreased due to the inflow of sandy-siltstone material from the shore. Below this section, gravelly sandstones with quartz-kaolinite cement were observed, which transitioned into gravels. The analysis of the K, U(Ra), and Th distribution curves and the GC diagram showed that the most abrupt change in sedimentation conditions occurred at a depth of 4,117 m. Below this level was a transitional rock stratum from the Visean to the Tournaisian deposits.

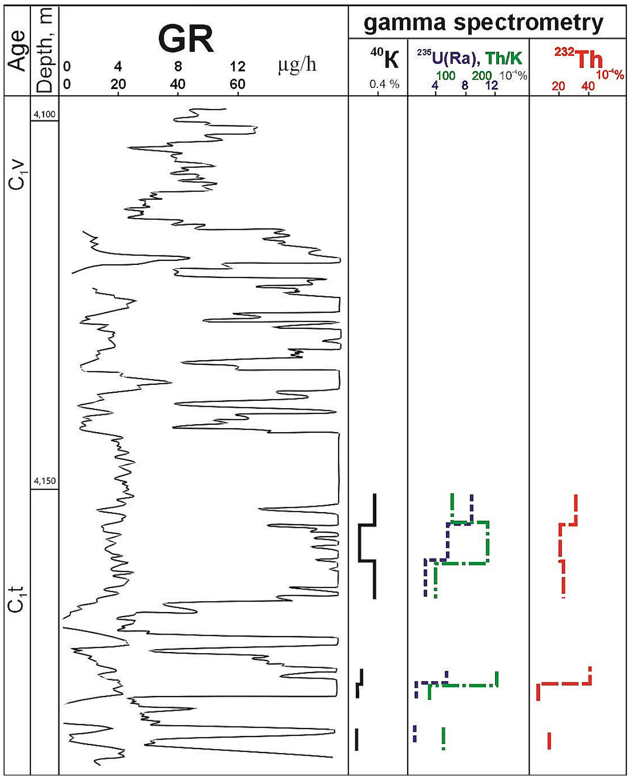

Figure 5. Well 1. The interval of exploration of depths 4,153-4,190 m

Source: made by the authors

Based on the fact that the Tournaisian rocks in the studied well sections within Plyskiv-Lysohorskyi outcrop were subcontinental and shallow, and the Visean rocks were marine, the boundaries between those stages could be taken by any coarse clastic rocks, any coarse fragmentary rocks that corresponded to short-term stages of intense erosion and faulting during tectonic impulses, the cover of the upper, light, gravelly or other sandstone in the Tuorniasian sequence that had kaolinite or quartz-kaolinite cement, indicating that the rocks were formed near the coastline separating the continent and the sea, the top of the upper red or variegated layer in the Tournaisian Formation marked the last shallowing, which led to the formation of rocks in an oxygenated (continental) environment, the top of the last upper Tournaisian layer of coal-bearing rocks (argillites rich in large carbonised plant remains, which were witnesses of the last bog regime, as well as by a geochemical parameter that indirectly characterised the predominantly acidic and alkaline conditions of sedimentation and separated strata formed in a substantially acidic environment during the subcontinental period of the Tournaisian. It was distinguished from strata formed in a substantially alkaline marine environment of the early Visean. According to the above, such a feature was the content of natural radioactive elements (K, U(Ra), Th), which were determined and confirmed in rock samples from wells within the Plyskiv-Lysohorskyi outcrop.

Thus, by comparing the absolute values of natural radioactive elements, the upper limit of the subcontinental and continental acidic regime of sedimentation of siltstone and clayey rocks was traced, and significantly overlapped by marine rocks accumulated under alkaline conditions. Each of the above conventional indicators reflected a specific geological and stratigraphic process, and therefore naturally had a different stratigraphic position (Fedak & Koval, 2020). The difference in the location of these geological levels determined the thickness of the transitional unit that arose from the change in sedimentation regimes. Practical calculations and comparison with the descriptions of the grinds showed the effectiveness of the method proposed by the authors for diagnosing only polymictic sandstones. The actual discrepancy of the stratigraphic position of the boundary in terms of physical parameters depended on the amplitude of tectonic oscillatory movements in each specific structure (Vysochanskiy *et al.*, 2022). The overall tectonic activity of the area, starting from the duration of the dominance of shallow and coastal sedimentation conditions, persisted until the continental regime was replaced by the marine regime (Stryzhak *et al.*, 2020). The comparative position of the stratigraphic boundary of the Visean and Tournaisian stages within the Plyskiv-Lysohorskyi outcrop is shown in Table 2.

Table 2. The position of the stratigraphic boundary between the Visean and Tournaisian stages of the Pliskivsko-Lysogorsk protrusion in the central part of the Dnipro-Donets Basin

Well	Location of the boundary between the Visean and Tournaisian stages by depth, m				
	According to the logging data	According to the upper boundary of the coal bed	According to the upper boundary of the mottled rock	According to the clastic rock with kaolin	According to radiometry data
Well 8	4,148	4,135	4,150	4,132 sandstone	4,125
Well 4	4,070	4,058	4,080	4,060	4,050
Well 3	4,765	4,759	-	4,765 breccia	4,765
Well 1	4,162	4,153	-	4,157	4,120

Source: made by the authors

Each of these stratigraphic boundaries was legitimate. However, given the high relevance of the geochemical parameter, it was recommended to accept the boundary of the Visean and Tournaisian stages at depths where there was a sharp change in the content of natural radioactive elements, in particular radioactive potassium, as well as the Th/K ratio. Determining the thickness of the transition layer between stratigraphic horizons was also of great practical interest (Streltsova & Kruhlyk, 2020). Based on the patterns of tectonic movements, it was possible to predict the predominant nature of these movements at different stages of their development. In particular, a regularity was identified that the thicker the thickness of rocks formed during the change from a continental to a marine regime, the more reservoir rocks could be observed in the geological section.

The advantages of using GR in combination with conventional electrical logging techniques for predicting fractured zones in foundation rocks were discussed in the work of E.O. Amartey *et al.* (2016). The authors noted that gamma logging significantly improved the accuracy of identifying zones characterised by specific resistivity minima, which could also be caused solely by lithological factors. According to L. Ke *et al.* (2023), the study of continental deltaic deposits characterised by strong lateral heterogeneity, while identifying the boundaries of such reservoirs, was complicated by rapid changes in rock properties. Accordingly, the authors proposed a new workflow for the integrated study of 3D geomodelling of thin-layered reservoirs. This procedure demonstrated good ability to characterise thin interstitial reservoirs only in continental deltaic deposits.

Researcher L. Yemets (2024), based on the results of geological and technological studies using the Komyshnianske gas condensate field as an example, demonstrated the possibilities of rapid lithological and stratigraphic sectioning, identification of reference horizons, determination of the nature of reservoir saturation, and determination of hydrodynamic and technological characteristics of reservoirs for testing facilities. All of this allowed obtaining data on the well section, performing correlation, determining the required completion depth, identifying reference horizons by cuttings, assessing the hydrocarbon saturation of reservoir formations, formation pressures, and selecting the perforation interval. However, in conditions of limited information, complex geological structure and the absence of a complete set of logging studies, additional studies are mandatory.

According to V.B. Volovetskyi *et al.* (2024), an information and software system was developed for the operational analysis of geophysical logging data from underground gas storage wells. The developed information and software systems were used to accumulate, verify, correct and analyse geological and geophysical information. The data from the developed databases were used to automate the process of creating graphical geological materials for each well and for the underground gas storage facility (UGSF) as a whole.

The purpose of the systems was to provide an automated solution for various geological and technological tasks: systematisation, accumulation, processing of information, and its graphical and documented display. The developed information and software complex allows displaying the results of lithological analysis of geological sections of wells and correlation of these sections of UGSF wells. However, this complex required a large amount of initial information. The possibilities of using spectral GR to solve the problems of sequence stratigraphy were discussed in D. Šimíček & O. Bábek (2015), where they studied siliciclastic rocks showing moderately high total radioactivity and average concentrations of K, U and Th. Heavy minerals were predominantly U and Th and therefore tent to be concentrated in argillites and sandy-muddy facies, while sandstone and conglomerate facies had slightly higher K levels due to higher content of K-feldspars and mica.

Researcher S. Machulina (2022) noted that methodological approaches to detecting hidden cycling in carbonate deposits were based on a comprehensive analysis of the results of geophysical surveys of wells and laboratory studies of the core samples collected using a cable core sampler. For example, in terrigenous deposits, where cyclicity was manifested mainly through gradual changes in the grain composition of rocks, lithological, mineralogical, petrographic and facies-geotectonic methods were used to identify sedimentary cycles (cyclites). In contrast, in thick terrigenous-carbonate and carbonate strata, discrete boundaries between cycles were usually fixed by thin layers of clayey rocks or brecciated limestone with inclusions of other rocks. Such horizons were valuable references for correlation between wells. The most reliable identification of large sedimentation cycles in carbonate deposits was provided by data from geophysical methods of well logging, including radioactive, acoustic and electrical.

From the above approaches, it is clear that each of them allows solving certain specific tasks of studying geological sections. However, the position of the boundary between stratigraphic units is more clearly established comprehensively using logging data, the upper boundary of the coal bed, the upper boundary of the mottled rock, the debris rock with kaolin and radiometry data. Accordingly, the lithological and stratigraphic dissection of poorly studied geological sections based on natural gamma-ray spectrometry can be used to trace the boundaries of the interface between sediments not only of the Visean and Tournaisian stages, but also of other lithological and stratigraphic horizons within the oil- and gas-bearing areas of Ukraine and the world.

Conclusions

Comprehensive lithological, petrographic, X-ray diffraction and gamma-ray spectrometric studies established a close relationship between the mineralogical composition of rocks, geochemical conditions of sedimentation and the content of natural radioactive elements (^{40}K, U(Ra), Th) within the transition strata of the Tournaisian and Visean age of the Plyskiv-Lysohorskyi outcrop crystalline basement. The distribution of natural radioactive elements in the rocks of the geological section corresponds to their mineralogical features and sedimentation conditions. The highest concentrations were observed in argillites, especially in siltstone and coaliferous varieties, due to the increased content of organic matter, kaolinite and iron hydroxides. The lowest values were in limestone and gravelly sandstone. The Th/K ratio proved to be the most sensitive parameter for establishing the stratigraphic boundary between the Tournaisian and Visean deposits. Its sharp change allows for more accurate localisation of the boundary between marine and continental sedimentation conditions, especially within the transition strata.

The lithological and stratigraphic heterogeneity of the transitional thickness was manifested in the sharp alternation of different-grained sandstones, argillites, siltstones and gravel-like formations, with frequent inclusion of carbonised organic matter and flint layers. This change in lithotypes confirmed the oscillatory nature of the sedimentation regime, reflecting the alternation of transgressions and regressions. The chemical and mineralogical composition of rocks indicates a gradual transition from acidic, subcontinental (Tournaisian) to alkaline, marine (Visean) conditions of sedimentation. In particular, the Tournaisian rocks showed a wider distribution of kaolinite, siderite, pyrite nodules and flinty argillites, while the Visean rocks were enriched with chemogenic silica, hydro-mica and minerals of hydrothermal origin.

Gamma-ray spectrometry proved to be an effective method of stratigraphic dissection by recording not only the absolute content of radioactive isotopes, but also changes in their ratios. In particular, it made it possible to localise the transition zone between stratigraphic units in wells 1, 3, 4 and 8, where other methods (macroscopic description, GC, CS) did not reveal a clear boundary. The stratigraphic boundary between the Tournaisian and Visean deposits is diffuse and is usually not accompanied by typical reference horizons (e.g., basal conglomerates or angular unconformities). Its position can be determined only based on a multifactorial analysis: petrographic, geochemical, mineralogical and radiometric. Thus, the results of the study confirmed the feasibility of using gamma-ray spectrometry in combination with lithological and petrographic analysis as an effective tool for stratigraphic correlation in conditions of complex geological structure. This allows not only to localise the boundary between stratigraphic units, but also to assess the nature of changes in the sedimentary environment, which is important for predicting the oil and gas content of the area.

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Conflict of Interest

None.

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Можливості літолого-стратиграфічного розчленування геологічних розрізів за даними спектрометрії природного гамма-випромінювання

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Анотація. Встановлення геологічної будови складнопобудованих осадових розрізів нафтогазоносних територій України, а саме їх літолого-стратиграфічне розчленування, є доволі складним і часто неоднозначним у трактуванні послідовності нашарування товщ осадових порід. Метою роботи було вивчення можливості літолого-стратиграфічного розчленування геологічного розрізу за результатами спектрометрії природнього гамма-випромінювання в інтервалі границь розподілу турнейських та візейських відкладів, у межах Плисківсько-Лисогорівського виступу кристалічного фундаменту приосьової зони Дніпровсько-Донецької западини. Методика вивчення границь розподілу турнейських та візейських відкладів базувалася на результатах розподілу концентрації радіоактивних ізотопів природнього гамма-випромінювання, отриманих безпосередньо у процесі буріння пошукових і розвідувальних свердловин. Окрім цього з інтервалів візейського та турнейського ярусів нижньокам'яновугільних відкладів відібрано керновий матеріал, проведено його літолого-петрографічне дослідження шляхом макроскопічного опису зразків керну, виготовлення й опис шліфів, а також виконаний рентгено-структурний і гамма-спектрометричний аналізи речового складу колекції зразків. У цілому визначалась кількісна наявність природних радіоактивних елементів. За результатами таких комплексних геолого-геофізичних досліджень було встановлено, що розподіл природніх радіоактивних елементів у інтервалах залягання відкладів, залежить від літологічного складу гірських порід, і відповідно зміни умов процесу осадконагромадження, що обумовлює зміни в розподілі радіоактивних елементів. Тому саме ця особливість будови може бути використана для прослідковування границь розподілу літотипів у горизонтах різних стратиграфічних товщ. Враховуючи те, що радіоактивність порід поліміктового складу характеризуються значним сумарним ефектом показу і зумовлена підвищеною радіоактивністю скелету матриці породи і глинистого матеріалу, який заповнює міжзерновий простір. Тому визначення глинистості доцільно виконувати з використанням результатів гамма-спектрометрії за величиною концентрації калію-40 або за даними гамма каротажу. Впровадження таких підходів у процесі інтерпретації окрім виділення границь розподілу між відкладами також дозволяє встановлювати фізико-геологічні умови, у яких проходив процес осадконагромадження різних літотипів гірських порід

Ключові слова: літотипи; колектора; спектрометрія; геологічна границя; осадконагромадження