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Evaluation of the influence of lithological and stratigraphic sections structure and capacitance-filtration parameters on the results of geophysical surveys of wells

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Abstract. Increasing hydrocarbon production from reservoir rocks of complex structure within the Neogene system of the Bilche-Volytske zone of the Precarpathian trough is a rather multifaceted problem that needs to be substantiated by conducting comprehensive geophysical, petrophysical and petrographic studies. The aim was to substantiate the physical-mechanical, electrical acoustic and petrophysical parameters based on the results of geophysical studies in a thin-layered Neogene section of gas and gas condensate fields within the Bilche-Volytske zone of the Precarpathian trough. The methodology for studying the complex Neogene sediments within the Bilche-Volytske zone of the Precarpathian trough was based on the quality of geophysical and petrophysical data obtained directly during drilling of exploration and development wells. In addition, the dominant role was played by the results of laboratory experimental studies of core samples, reflecting reservoir thermobaric conditions. Based on the results of such comprehensive geological and geophysical studies, it was established that the readings of geophysical methods are significantly affected by the thin-layered structure of the geological section, which is lithologically represented by the interlayering of sandstones, siltstones and mudstones. It has been found that the downhole instruments used in geophysical expeditions have a significant impact on the readings of geophysical methods. Accordingly, the research results are aimed at improving the efficiency of hydrocarbon exploration and control of their extraction. Therefore, the availability of highly informative integrated geophysical surveys, in particular, multi-probe acoustic logging, high-frequency induction logging isoparametric probing and repeated neutron logging, allows optimising conclusions regarding the prospects

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for hydrocarbon discovery in complex thin-layer sections. The introduction of new approaches to the identification of such layers and strata will improve the information content of geological and geophysical methods and increase the hydrocarbon yield within the Bilche-Volytske area of the Precarpathian trough

Keywords: lithotypes; reservoir; porosity and permeability coefficients; electrical resistance; pores; acoustic impedance; electrical and acoustic probes

Introduction

The issue of increasing hydrocarbon production in the western region of Ukraine is linked to the known oil and gas bearing zones where commercial oil and gas reserves have already been proven. These zones include the Krukenytsia sub-zone of the Bilche-Volytske zone of the Precarpathian trough, where a number of gas fields have been discovered. These deposits are confined to anticlinal structures of the Upper and Lower Dashava sediments of the Neogene system, inherited and covering the uplifted areas of the Miocene basement, the erosion relief of which is controlled by the gypsum anhydrite horizon. The study of such complex reservoir rocks by geophysical methods of well logging is sometimes difficult. This applies to the interpretation of electrical and acoustic readings, which do not fully correspond to the actual geophysical parameters of the formations that fill the Neogene section. Establishing the influence of rock matrix skeleton composition, type of fluid saturating them, presence of bound water and the other characteristics on physical and petrophysical values of reservoir rocks allows to increase the efficiency of geophysical surveys. Increasing the information content of the results of comprehensive geophysical surveys of complex reservoir rocks will help identify additional promising hydrocarbon accumulation sites, which will allow increasing their reserves.

Many scientists have been studying the deep structure of the sedimentary layer and determining the prospects for oil and gas in the Krukenytsia Basin. In particular, Y. Krupskyi (2020) pointed out the peculiarities of the geodynamic development of the Bilche-Volytske zone and outlined the prospects for oil and gas content of the stratigraphic section. He also highlighted a new interpretation of the main regularities in the location and formation of hydrocarbon deposits from the perspective of the geodynamic development of the Carpathian Region. S. Anikeyev & S. Rozlovska (2021) analysed in more detail the features of the deep geological structure of the subsoil of the western region of Ukraine based on seismic surveys and proposed further directions for oil and gas exploration based on seismic data. In addition, the geological informativeness of the morphology of anisotropic transformations of potential fields in the study of fault tectonics of the Ukrainian Carpathians and adjacent depressions was clarified. The work of M. Pavlyuk *et al*. (2021) substantiates the formation of tectonic faults and the creation of structural objects with prospects for hydrocarbons. The main attention is paid to hydrogeological criteria for assessing oil and gas prospects on the example of substantiation of new prospecting objects in the platform autochthon under the Pokuttia-Bukovyna Carpathians thrust.

In the works of S.S. Kurovets *et al*. (2018) and O.M. Karpenko *et al*. (2021), low-porosity productive rocks of the Sarmatian sediment reservoirs of the Precarpathian trough were identified, their petrophysical parameters were substantiated, and the patterns of deviation of fluid filtration parameters through low-porosity rocks from Darcy's law were established. Based on the data from the well logging and using statistical methods of studying the lithological and facies dissection of the oil and gas reservoir, statistical relationships between natural radioactivity and organic carbon content were established. Y.M. Koval & I.O. Fedak (2022) identified promising areas with favourable structural, tectonic and paleohydrodynamic conditions for the formation of hydrocarbon deposits in the sediments of the Lower Dashava and Upper Dashava sub-suites. Also, M. Yershov *et al*. (2022) conducted research on the study of temporal patterns of time series trends of data from hydrogeological monitoring stations located in the Carpathian Region, which is a cross-border territory of Ukraine. Based on the results of the studies, the researchers found that the low resistivity of the reservoir layers of Neogene sediments is caused by the electrical conductivity of the grains of rock-forming minerals, namely pyrite and chlorite.

In the process of saturation of complexly constructed thin-layered sediments of the Sarmatian, Badenian and Helvetian stages of the Neogene system, the results of well studies using traditional methods are affected by an ambiguous assessment of the nature of saturation with potentially oil and gas-saturated reservoir rocks. Accordingly, the purpose of the study was to identify the factors that cause ambiguity in the thin-layer section and to unambiguously identify productive horizons in the course of well logging, which leads to the omission of productive gas-saturated reservoir rocks. Accordingly, the task was to evaluate the quality of the results of the geophysical survey used to dissect a thinly layered geological section, taking into account the mineralogical structure of the rock matrix, the nature of their saturation and their impact on the readings of geophysical methods. In addition, it was necessary to substantiate and adapt filtration and capacitance parameters to similarly complex reservoir rocks in neighbouring exploration and production fields.

Materials and Methods

In the course of prospecting and exploration of reservoir rocks formed under different conditions of sedimentation in lithological and stratigraphic sections and hydrocarbon-saturated traps within the Krukenytsia depression, a number of tasks arise that are solved by means of geological logging. Given the complexity of the geological structure of the prospecting and exploration areas of the Bilche-Volytske zone, it became necessary to substantiate the geological structure of the gas and gas condensate fields that are promising for hydrocarbons (Kurovets *et al.*, 2021). In the course of the study, it was necessary to take into account and detail the project for drilling exploration wells, including reference wells with maximum core sampling. On the basis of the selected core, an experimental collection of samples was formed that meets the requirements of mathematical statistics (GSTU 41-00032626-00-025-2000, 2001). Rock studies included determination of the chemical composition of rock-forming minerals, their structure, establishment of conditions of their formation, quantification of the content of basic minerals, structural features and presence of micro-impurities. To identify the main radioactive elements (U(Ra), Th, and K), nuclear-physical studies were used to determine the distribution of radioactive isotopes in a thin-layered section with sand layers from 0.15 m to 0.45 m thick in Neogene deposits of gas condensate fields in the Bilche-Volytske zone of the Precarpathian trough (Fedoryshyn *et al.*, 2015).

Taking into account the geological heterogeneity of the Neogene sediments of the Bilche-Volytske zone of the Precarpathian trough, the core material was studied by comprehensive petrophysical research. First of all, a granulometric analysis was carried out to separate sand (> 0J mm), siltstone (0.1-0.01 mm) and clay (< 0.01 mm) fractions. The granulometric analysis is based on the distribution of clay and sandy-siltstone fractions in the core, which is carried out by washing and settling in water and sieving the fraction > 0.01 mm on sieves. A particular feature of particle size analysis is the need to destroy the rock structure to separate it into mineral grains, fragments and cementing particles. Core testing for carbonation (C_c) was carried out using hydrochloric acid. The volumetric method was used for the study. It is based on determining the volume of carbon dioxide (CO_2), which was released after the reaction of the carbonate component with hydrochloric acid (HCI). Absolute permeability (K_{ap}) is measured on cylindrical samples by the method of stationary filtration at different differential pressures. Open porosity measurements were also carried out (K_p) by the weight method by saturating cylindrical core samples with kerosene. The residual gas saturation was modelled on the core samples using the centrifugation method by obtaining a capillary pressure curve for the sample with residual water saturated with kerosene. The specific electrical resistivity of fully and partially water-saturated rocks and the specific electrical resistivity of formation water (model) were also measured to calculate the porosity parameter P_p and the saturation parameter P_s. These parameters are the main characteristics for constructing petrophysical dependencies of the type $P_p = f(K_p)$, $P_s = f(K_s)$, which were used for operational interpretation of the geophysical methods of well logging.

The results of the research are the basis for the future identification and evaluation of specific productive gas and gas condensate-saturated reservoirs within the lithological and stratigraphic exploration sections (Ivaniuta, 1998). It should also be noted that the effectiveness and reliability of the established geophysical and petrophysical parameters will be affected by the value of reservoir pressure, temperature and physical and mechanical parameters of the stratified rocks. In addition, the structure of lithotypes is influenced by the presence of a rift structure that stretches along the Krakovets Fault, from the Polish-Ukrainian border, in a strip of several to 10 km. Thus, to solve the tasks set, the results of well logging in the wells of the Vizhomlia gas field were analysed, namely the section of Neogene sediments, where intervals of gas and condensate saturated formations, which are mainly represented by sandstones and siltstones, were identified. The completed geophysical survey consisted of a mandatory set of well logging data, which allows to successfully solve both general geological tasks of lithological dissection and correlation of geological sections and to establish industrial and geophysical characteristics (identification of reservoir rocks, determination of their porosity, effective thickness, oil and gas saturation, and contact mapping).

Processing and interpretation of the source materials of the well logging data begins with the division of the geological section into layers and strata, which starts with the identification of the boundaries of the layers and determination of their reservoir characteristics. The task is solved with the help of computerised Geoposhuk technology (Krasnozhon *et al.*, 2003). The processing process consists of several successive processing stages: section splitting into layers and interlayers, determination of the resistivity of these layers and the flushing fluid, quality assessment of well logs, evaluation of the filtration capacity of rocks, identification of reservoir and cover rocks and determination of their saturation. The construction of a correlation geological section begins with the formation of an integrated working database, which is loaded into a window for operational interpretation. The next stage is the construction of geophysical data sheets, where the section was divided into layers and interlayers and the quality of logging materials was assessed. Comprehensive interpretation begins with an assessment of the filtration and reservoir properties of rocks and reservoirs using a universal formula interpreter, and a geophysical conclusion is generated based on the results of logging interpretation. As a result of the consolidated interpretation of the logging data, a correlation geological profile was built along a given well line. The porosity coefficient, physical and mechanical parameters, and rock matrix compression ratio are calculated using the following formulas:

$$\beta_{rm} - \frac{1}{V}\left(\frac{dV_p}{dP}\right)P_{rp}^t;$$
$$\beta_{por} = -\frac{1}{V_{por}}\left(\frac{dV_p}{dP}\right)P_{por}^t, \quad (1)$$

where β_{rm} and β_{por} are, respectively, the compression ratio of the rock matrix and its void space. Taking into account that rock-forming minerals are characterised by a low value of the compression coefficient in the rock matrix, the most informative is the void compression coefficient. This coefficient changes with depth according to the hyperbolic law (Dentith *et al*., 2020). The porosity parameter of reservoir rocks decreases at a reservoir pressure of 150 MPa to 17-18%. With the increase of saturation of gas-saturated reservoir rocks with water under conditions of increasing effective pressure and temperature, the specific electrical resistivity increases. In this case, the calculation of the resistivity of the rock is performed by the following differential equation:

$$\frac{d\rho_p}{\rho_p} = \frac{1}{\rho_p}\left[\frac{d\rho_p}{dP_{ef}}\right] P_{rp}^{t^0} \times dP_{ef} + \frac{1}{\rho_p}\left[\frac{d\rho_p}{dP_{rp}}\right] P_{ef}^{t^0} dP_{rp} + \\ + \frac{1}{\rho_p} \times \frac{d\rho_p}{dt} dt = K_{rm} dP_{ef} - K_{elw} dP_{rp} - (\alpha t)\rho dt, \quad (2)$$

where K_{rm} – coefficient of relative change in specific electrical resistance per unit of effective stress determined by isothermal pressure; ρ_p – electrical resistivity; $P_{rp}^{t^0}$ – reservoir pressure with temperature at a given depth; P_{ef} – effective pressure within the reservoir; K_{elw} – coefficient of change in electrical resistivity of water per unit change in reservoir pressure; αt, ρ – coefficients determined by isobaric heating or cooling of water-saturated rock with temperature change. In an approximate form, the equation for the relationship between the resistivity of reservoir rocks in Neogene deposits, taking into account reservoir pressures, will be as follows:

$$\frac{\rho_p(P_{rp}t^0)}{\rho} \approx \frac{\rho_{r_{ef}} - \rho_{r_{rp}}}{\rho_{ac}} \times \frac{\rho_{r_{rp}}}{\rho_{ac} P_{rp}} \times \frac{\rho_{ef}^{t^0}}{\rho_{ac}}, \quad (3)$$

where $\rho_p(P_{rp}t^0)$ – the resistivity of the rock in reservoir conditions; ρ_{ac} – the resistivity of the rock under atmospheric conditions; $\frac{\rho_{r_{ef}} - \rho_{r_{rp}}}{\rho_{ac}}$, $\frac{\rho_{r_{rp}}}{\rho_{rt}}$ and $\frac{\rho r_{ef}}{\rho(P_{rp})}$ – relative changes in the resistivity of the rock under effective and reservoir pressures $P_{ef} - P_{rp} = const$; $\rho_{r_{pt}}$, ρ_{r_p} – resistivity at the initial and current pore pressures. In order to exclude the influence of the resistivity of the free fluid on the porosity parameters, the following formula can be used:

$$\frac{P_r^{ef}}{\rho_p} \approx \frac{P_p^{P^{ef}}}{P_p} \times \frac{P_p^{P_{in}}}{P_p^{rp}} \frac{P_{rp}^t}{P_{ef}}, \quad (4)$$

where $P_p^{P_{rp}t}$ – the parameter of rock porosity with specified thermodynamic conditions; P_p – similar parameter at initial atmospheric conditions; $\frac{P_p t}{P_p}$ – a ratio that characterises a partial change in the porosity parameter due to the influence of temperature.

Results and Discussion

The effectiveness of productive reservoir identification and tapping and interpretation of the logging results largely depends on the study of lithological and petrophysical characteristics of reservoir rocks, physical and chemical properties of fluids, technological conditions of drilling, reservoir pressures and temperatures, and the reliability of stratigraphic sectioning of the studied sections. The geological structure of gas fields in the Bilche-Volytske zone is based on Miocene terrigenous sediments that are inconsistently located on terrigenous carbonate platform Mesozoic complexes. These sediments differ in terms of sedimentation conditions and physical and petrophysical characteristics of reservoirs and bedrock. The main difficulties that arise in the process of studying Miocene sediments by geophysical methods are their thin-layered structure, high clay content of sandstones and polymicticity. Such structure and physical and petrophysical features of rocks are inherent mainly in the deposits of the Neogene system, which is represented by overburdened rocks of the Stebnytsia and Balytska formations, as well as autochthonous deposits of the Carpathian, Badenian and Sarmatian. A characteristic feature of the sediments that make up the Carpathian stage is the low resistivity of sandstones and the diversity of their mineralogical composition. In order to study the rocks and their characteristic features, comprehensive studies allowed to develop a classification of these sediments and determine their geophysical and petrophysical characteristics.

According to the mineralogical description of polished sections made from the core samples of the Carpathian sediments and the analysis of the results of nuclear-physical studies, the following classification types can be distinguished. Sandstones are represented by the following types: gravelly sandstones with chlorite-calcite and chlorite-clay cement, sandstones of different grains with chlorite-clay cement, medium-grained sandstones with calcite cement containing single grains of glauconite, fine-grained sandstones with chlorite-clay, chlorite-calcite, calcite-clay and calcite cement containing single glauconite grains, and siltstone with clay-calcite cement. Siltstones are gravelly-sandy with clay-calcite and chlorite-clay quartz cement. The mudstones are calcareous. In most of the exploration areas, oil, gas and condensate deposits are confined to quartz, feldspar sandstones, siltstones, clay shales, limestones and dolomites cemented with clay-carbonate, halite and mixed cements (Bulakh *et al*., 2022). The void space of this type of terrigenous, thinly laminated rocks of complex structure is represented by intergranular pores and cracks, which were obtained from the created collection.

The identified rock types mostly differ in the ratio of clastic components and cement composition, which is due to ancient changes in the supply of clasts, which now determine the reservoir properties of the rocks. Fine-grained sandstones with hydromica-clay cement formed during this period (well 5-Letnia 1,607.3 m deep) consist mainly of wedge-shaped and semi-rounded quartz fragments (70-80%) with a size of 0.3-0.1 mm. Most of the quartz particles have wave attenuation and traces of compression, which indicates that they were removed from ancient metamorphosed rocks. Among quartz, there are single fragments of zircon and muscovite. The fragments are cemented by an unevenly hydro-mica-clay aggregate, which has a filmy structure, and the pore space structure is clotting. Hydromica in the form of clumps up to 0.1 mm in size (5-8%) covers quartz fragments with films or sticks to them, rarely forming a mixture with a fine clay substance containing, in some cases, small pieces of illite. In the authors' opinion, such layers were formed in a coastal environment with good sorting of debris against the background of rapid bottom sinking and sedimentation, which kept the debris from rounding. Although the porosity of the rock is low, there may be good collector rocks alongside these rocks, which were formed on ancient bars, beaches, and shoals.

Fine-grained sandstones with chlorite-glauconite-clay cement contain fewer fragments deposited during the formation period. Compared to the sandstone described above, the bulk of the rock is composed of angular and semicircular quartz fragments with 65-75% quartz, often closed to each other. Particles with a size of 0.3-0.5 mm make up approximately 10-5%, 0.3-0.1 mm, 40-50%, and 0.1-0.05 mm, approximately 3-8%. The distribution of fragments is chaotic (Fig. 1). The cement of the rock is mainly clayey, finely dispersed, and striped. In the bulk of the clay substance, fragments of hydrochloride (2-3%) are sometimes found near quartz fragments. In addition, there are dark green chlorite-glauconite inclusions of irregular shape, rarely in the form of round peas, the size of which is close to the size of the fragments, between the fragments. There is an indentation of the fragments into green clots of glauconite inclusions, which indicates their consedimentary nature.

Figure 1. Fine-grained sandstone with chlorite-glauconite clay cement

Source: created by the authors

Sandstones with chlorite-calcite cement are similar in composition to siltstone types. They are composed mainly of quartz fragments (55-70%), with less wedge-shaped fragments than clayey varieties. The sorting of fragments in such rocks is better; in cement, chlorite and glauconite are closely fused together to create irregularly shaped clots. Pyrite inclusions are observed alongside and within these clots. The distribution of chlorite and glauconite is uneven, with their content reaching 1-5% in different areas. The calcite in the cement is granular and well crystallised. The grain size is 0.1-0.3 mm. In some areas, the grain size reaches 1 mm and a poikilite structure appears; in some places, quartz grains are intensively destroyed by calcite on the periphery and along individual cracks. Such sandstone is a poor reservoir, as calcite is additionally subject to partial recrystallisation and compaction. Increased porosity of such rocks can be expected in places where various fragments of siltstone are found among quartz fragments. The latter may indicate consedimentary erosion of the shoal, hydrodynamic activity of water, and better sediment washing.

According to the description of the grinds, a silty, multigrained sandstone with clay-calcite cement formed under the same conditions consists of quartz fragments that differ significantly in size and grain sorting. Individual grains do not touch each other and are often unevenly scattered. The amount of fragments and cement is 45-55%; the cement is fine-crystalline and crystallised and unevenly distributed. In some places, calcite grains are 5-7 mm in size, round or amoebic in shape, and usually fill the intergranular space of large pores (about 5%) and cement a number of quartz fragments to form poikilite structures. In some cases, single inclusions of pyrite are found in such sandstones, and there are areas where its content reaches 1-5%. The rock has uneven porosity. The pores are mostly intergranular and distributed along microcracks; their size reaches thousandths of a mm. There are also large pores of 0.1-0.2 mm in size, rarely larger. The rocks were formed mainly in shallow lagoonal conditions, which resulted in their good reservoir properties.

At the same time, silty sandstone with chlorite-calcite cement is mostly composed of 50-70% quartz fragments, the particles of which are mostly angular, poorly sorted and have a size of 0.6-0.1 mm. A small part of this type of rock consists of semi-angular, semi-rolled fragments, which usually do not touch each other. Some of them have a wave-like extinguishment and are intersected by quartz veins. The rock contains single fragments of zircon, albite and staurolite. The cement is mainly calcite of the basal type; the pore space is filled with grains of crystallised calcite. In addition, single pyrite clots are present in the cement. The rock was formed in lagoonal conditions in a low-reducing environment with rapid sedimentation. As a rule, it has poor reservoir properties, but in the horizons closer to the shore, rocks with high filtration properties can be expected. In the core samples taken from the Sarmatian deposits, there is a hidden, uncoordinated overlay of siltstone with calcite cement (light areas) on sandy siltstone with calcite-clay cement (dark areas) (Fig. 2). Clumps of clay (dark) are observed at the boundary of these rocks, with quartz fragments more massive than the bulk of the overlying sandstone.

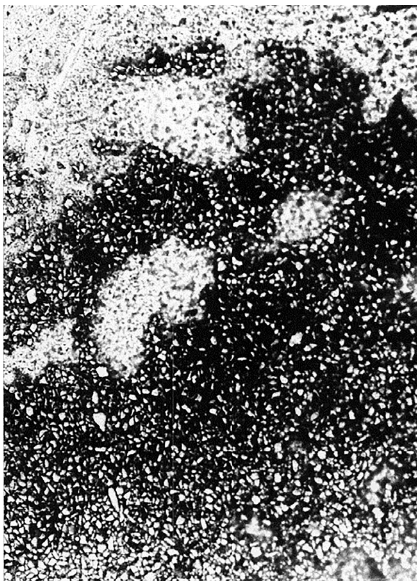

Figure 2. Sandy siltstone with calcite-clay cement

Source: created by the authors

The facies transition at the interbeddedness of silty sandstone with hydromica clay cement into silty mudstone (Fig. 3) clearly shows a gradual decrease in the amount of small fragments at the sandstone-silty mudstone interface. Quartz fragments are well sorted, fine-grained, and up to 0.5 mm in size, accounting for 1-2%. The sandstone cement, like the bulk of the mudstone, consists of a finely dispersed, poorly crystallised hydromica-clay aggregate. The hydromica clay mass is enriched with pyrite by 5-15%.

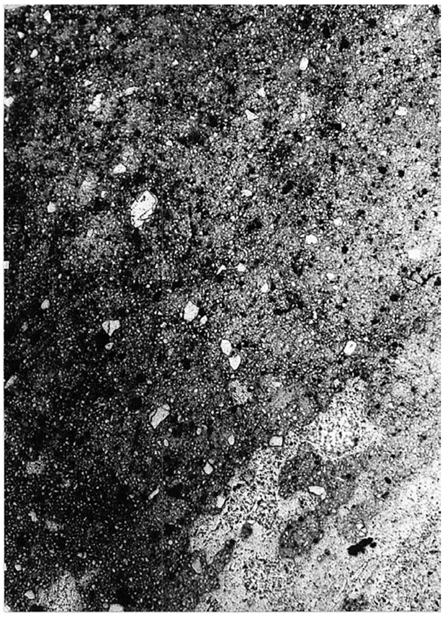

Figure 3. Silty sandstone with hydromica clay cement

Source: created by the authors

Along with small pyrite cubes, there are more massive rounded clots 0.001-0.005-0.03 mm in size. In some places, there are brownish clots, fragments of montmorillonite with a weakly pronounced concentric and compression-deformed structure. Judging by the slight difference in the size of the fragments, it can be assumed that the coastline moved a short distance, and changes in rock formation were determined by the submergence of the basin floor and an increase in its depth in this area. With regard to the mineralogical composition and structure of the siltstone, it was found that the sandy siltstone with glauconite-clay-calcite cement consists mainly of fragments of well-sorted siltstone material. This feature of the structure indicates sedimentary consedimentation and the demolition of more massive fragments to the place of rock formation by currents. The sand fraction in the rock is insignificant and amounts to 1-5%. Comprehensive geophysical surveys performed both in the open hole and in the cased hole allowed to highlight a number of physical and petrophysical factors that significantly affect the readings of radioactive, acoustic and induction methods (Ganat, 2020). As can be seen from the correlation profile (Fig. 4), a number of reservoir rocks with characteristic petrophysical and geophysical parameters are observed within the complexly constructed Neogene sediments.

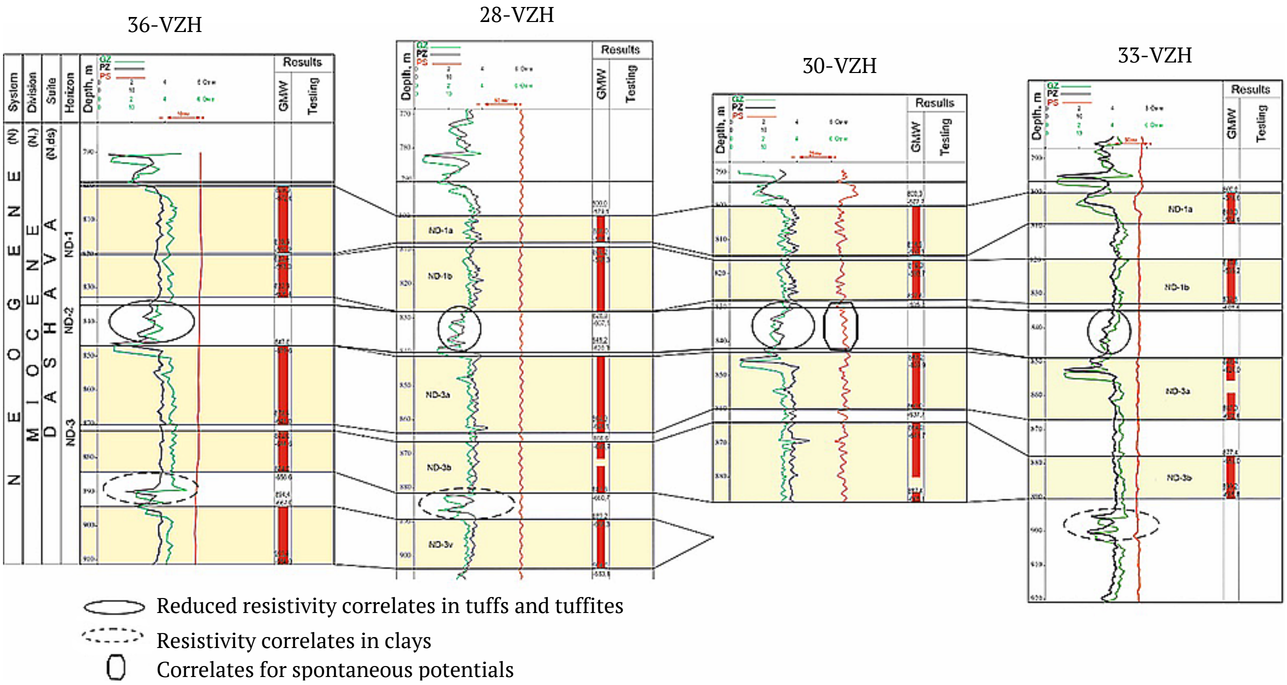

Figure 4. Correlation profile along the line of wells 36-Vzh-28-Vzh-30-Vzh-33-Vzh

Source: created by the authors

When constructing the correlation profile, the results of the well logging were taken into account, as were the established petrophysical capacitive and filtration parameters, which allowed to assess the prospects for oil and gas condensate reservoirs. Given that the presence of physically bound water, including crystalline bound water and residual oil, was found in reservoir rocks, it can be argued that their content will also affect the readings of electrical, acoustic and radioactive methods (Kuzmenko *et al.*, 2019). This is especially true for sandstones and siltstones in the geological sections of the Svydnytsia, Vizhomlia and Lypovets fields (Ftemov *et al.*, 2021). The rock types that were identified are mostly distinguished by their characteristic structure, the ratio of fragmentary components and cement composition, which determine reservoir properties (Dubei *et al.*, 2022).

It should also be noted that fine-grained sandstones are mainly characterised by the presence of chlorite-glauconite cement, which will also affect, along with the coefficient of bound water and residual oil, the electrical and radioactive parameters of geophysical methods. Sandstones with chlorite-calcite cement, which are similar in composition to siltstone varieties, are also gas and condensate reservoirs (Cannon, 2015). Their structure is similar to sandstones and consists of 55-70% quartz fragments, mostly semicircular and angular. This is mostly typical for the Letnia field (well 5 Letnia, depth 1,988.5 m; 1,579.0 m; 1,592.5 m), where wedge-shaped quartz fragments are less abundant than clay minerals of various types. The sorting of this type of fragment is better, but the cement material consists of chlorite and glauconite, which are closely fused together to create irregular shapes. Pyrite inclusions also appear in the middle of these clusters. The distribution of chlorite and glauconite is uneven, but their content reaches 1-5% within the Neogene sediments. Thus, in addition to the above, the readings of complex geophysical surveys, in particular electrical and radioactive, will be affected by the above minerals and the coefficients of physically bound water and residual gas and oil saturation. In addition, depending on the structural structure of the reservoir rock and the value of the porosity coefficient, the physical and mechanical parameters will be deformed under the influence of the pressure gradient and the matrix compression ratio (Dubei & Dubei, 2023).

The value of the coefficient K_{rm} is determined provided that P_{rp} and t^0 – *const*. Taking into account the shallow depths of Neogene sediments, as well as insignificant compression of the solid phase of reservoir formation in the processes of hydrocarbon accumulation, it can be stated that in the zones of reservoir pressure depression, it does not significantly change the coefficient K_{rm}. In this case, the value of the coefficient K_{rm} for sandstones and siltstones is determined by the established value of the effective stress that causes a change in the tortuosity of pore channels and, accordingly, their moisture content (Fig. 5). It should be noted that the coefficient (αt) will depend on changes in the electrical conductivity of free and physically bound water in reservoir rocks, pore geometry and volume, temperature changes, and the presence of thermally conductive inclusions. Based on the results of laboratory petrophysical studies of the selected core samples, graphs of the relative electrical resistivity were constructed (Cannon, 2015) versus pressure change for polymict and monomict pressure rocks.

As can be seen from the plots for individual resistivity ratios, changes in pressure will not affect changes in relative electrical resistivity. However, in the range of reservoir pressure changes from 20 MPa to 60 MPa, which is typical for the structure of Neogene deposits, the relative resistivity will increase with increasing reservoir pressure as well as with changes in temperature at a given depth. Thus, it was found that a pressure change of up to 50 MPa has virtually no effect on the porosity parameter P_p (Dubei & Dubei, 2023). Considering the above, the following can be written:

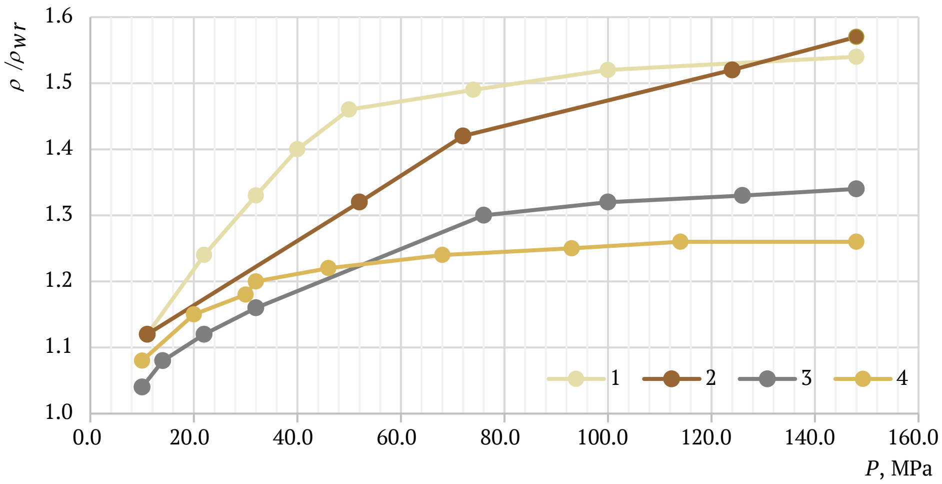

Figure 5. Relative change of relative electrical resistivity with pressure for polymict-type reservoir rocks

Note: 1 – fine-grained quartz-feldspar sandstone with carbonate-clay cement; 2 – fine-grained quartz-feldspar sandstone with clay cement; 3 – medium-grained quartz sandstone with clay cement; 4 – medium-grained quartz sandstone with clay-carbonate cement

Source: created by the authors based on O. Trubenko & S. Fedoryshyn (2011)

$$\frac{P_p^{ef}}{P_p} = \frac{P_r^{ef}}{\rho_p}. \quad (5)$$

By substituting expression (4) into formula (5), an expression was obtained that allows to estimate the relationship between the porosity parameter and the value of the rock resistivity depending on the nature of its saturation. Summarising the results of the core material studies, the following expression can be stated:

$$\frac{{P_p}^{P_{rp}t}}{P_p} \approx \frac{{P_p}^{P_{ef}}}{P_p} \times \frac{{P_p}^{P_{in}}}{{P_p}^{P_{rp}}} \times \frac{P_{rp}^t}{P_{ef}}, \quad (6)$$

where $\frac{{P_p}^{P_{ef}}}{P_p}, \frac{{P_p}^{P_{in}}}{{P_p}^{P_{rp}}}$ are, respectively, the ratios that highlight the partial changes in the rock porosity parameter under the action of the effective stress under the conditions $P_{in} = const$, $P_{ef} = 0$, $t = const$. The obtained equations describe the relationship between the rock porosity parameter and its resistivity within the Neogene deposits of the Bilche-Volytske zone of the Precarpathian trough and can be used to evaluate the results of electrical studies, as well as to increase the informativeness of petrophysical parameters of mathematical and statistical correlations in the process of calculating hydrocarbon reserves. In the process of searching for hydrocarbons in thin-layered Neogene formations using integrated geological and geophysical methods, there is often a problem of identifying reservoir rocks, assessing their saturation, determining porosity, and permeability. As a result, a significant proportion of hydrocarbons is lost, which leads to a decrease in actual gas and condensate production within the exploration areas at the stage of exploration drilling. Experimental studies of the core collection of rocks that fill the Neogene section allowed to determine their structural structure, petrophysical parameters, cement type and mineral composition of clay cement. In most cases, within the exploration geological areas filled with the Sarmatian formation, significant fracturing, bulk and interlayer clay, polymicticity are observed in some places, and in some intervals, significant residual water saturation is noted in the rocks.

Based on this, the existing search complex of well logging data is not informative in some cases. In particular, this applies to acoustic and electric well logging, which are basic in the process of identifying reservoir rocks and assessing their hydrocarbon saturation. Acoustic surveys of thinly layered Sarmatian sediments are mainly carried out with single-probe and dual-probe probes (DALT-4, 6, 8, 9). Taking into account that the dependence of the interval time of acoustic oscillations does not allow obtaining accurate information about the type of porosity (granular, cavity, fracture), as well as the nature of saturation, the morphology of the results obtained loses its informative value. In this case, the Willy-Gregory formula, as well as the constructed two-dimensional petrophysical dependence of the $\Delta T = f(K_p)$ type, does not give reliable results, and the recorded acoustic logging curve is not informative; therefore, the indicated constructions based on theoretical calculations showed significant differences in the porosity curves, despite the same initial data.

Such a discrepancy is explained by the fact that the time of the ultrasonic longitudinal wave travel through the rock, depending on the change in the porosity value, obeys the minimum law at a conditional value of 40-45%; the wave propagation speed in the rock is equal to the wave speed in water. Therefore, the relationship ($Vp = Vw$) has a rather complex shape and is usually not linear. Thus, when the rock porosity is higher (30-35%), the longitudinal wave velocity will be close to its propagation in water. In real conditions, the propagation speed of an ultrasonic wave obeys a different law, i.e. it depends on the density of rock grains, mineralogical composition and type of porosity. Based on the above, it is recommended to use acoustic borehole devices in the process of complex acoustic surveys DAT-1, BAL-4,6. In some cases, it is not possible to determine the gas or oil saturation of reservoir rocks using standard electrical methods. Physically, this occurs when different concentrations of drilling mud come into contact with a constant rock solution, which changes the diffusion potential (U_d) and increases the resistivity according to the formula:

$$U_d = K_d \times lg \frac{\rho_1}{\rho_2}, \quad (7)$$

where ρ_1 – a resistivity of the NaCl solution; ρ_2 – resistivity of the solution formed in the rock; K_d – diffusion coefficient. Therefore, an increase in the concentration of chemical reagents in the drilling mud causes sharp changes in the diffusion-adsorption potential, such as an increase in the concentration of NaCl. Therefore, chemicals are used in the drilling process (CSC, CMC and hypan), which are weakly alkaline or alkaline in nature and have a much lower oxidation capacity, and, accordingly, the potential of clays, which leads to changes in the potentials of sandstones and siltstones. In this case, the informative value of direct methods, in particular, spontaneous potentials (PS).

A widespread set of electrical geophysical survey methods that solve the problem of hydrocarbon exploration are the standard methods (BKZ, BC, IR, PS), which are called isoresistive interpretation methods. The most effective is the method of high-frequency induction logging isoparametric sounding (HFILS). Unlike the above-mentioned set of electrical methods, the principle of operation of the HFILS method is based on high frequencies and provides high-resolution recording of electrical properties of the borehole zone and rocks of the geological section in the radial and vertical directions of the well. Therefore, the use of high frequencies makes it possible to obtain clear signals even in a low-conductivity environment (up to 120 ohms). This method of determination is not affected by the concentration and composition of chemicals used in the well completion process.

G. Sun *et al.* (2023) described the results of a detailed study of a thin section core, thin section analysis, mineral analysis and geochemical analysis to investigate thin layers and nodules of dolostone in the Qingshankou Shale in Gulong Sag. The geological structure and development of thin layers and nodules of dolomite is associated with the dry and hot climate of the sediments and was formed under the influence of hydrothermal fluids. These studies were carried out on the example of thin layers and nodules for dolomite deposits. Neogene deposits of gas fields in the Bilche-Volytske zone also have a thin-layered structure but are represented by a terrigenous section and, accordingly, the research methodology is somewhat different from that for a carbonate section. Considering the work of X. Qiu & Y. Wang (2024), attention should be paid to the study of sedimentary rocks, the characteristics of the reservoir of which are described and studied in detail using conventional grinds, cast grinds, graphical representations of particle size and scanning electron microscopy experiments. These studies were conducted using sedimentology and sedimentary geology, which are used to analyse the sedimentary environment of the basin. These studies have made little or no use of the logging data, and therefore such sedimentary models should be supplemented with geophysical characterisation.

F. Olita *et al*. (2023) carried out a geological analysis based on the results of new lithological and structural data obtained during a detailed geological survey and supplemented by logging data obtained during hydrocarbon exploration. The geophysical surveys were carried out at a depth of up to 1 km (deep electroresistive tomography), which revealed the buried structural and geological characteristics of the study area. By combining surface and subsurface data, a forecast of the structural situation and the presence of geofluids at a depth of up to 1 km was made. Geological and structural cross-sections were also constructed to clarify the geometry of structures in the subsurface, facilitating early hydrocarbon recovery and circulation of hypothermal fluids and associated gases rising from deeper reservoirs. These studies have been carried out to a depth of 1 km, while hydrocarbon deposits in the Bilche-Volytske zone of the Precarpathian trough lie at somewhat deeper depths and require a different approach to their study.

The core material from 28 wells in the central part of the Dnipro-Donetsk Basin was studied by L. Stryzhak *et al.* (2020) using lithological and petrographic methods. The results of the study confirmed the processes of lithogenetic transformations of the rock matrix that occurred in deeply submerged sandstones (more than 5,000 m). Based on the nature of structural and mineralogical transformations, the secondary (post-sedimentation) processes of lithogenesis of terrigenous rocks-collectors of hydrocarbons were established, and their influence on the reservoir properties and, accordingly, on the reflection in geophysical parameters was revealed. Such studies need to be linked to the geological logging data to fully understand the processes of secondary transformation of the reservoir rock matrix.

Similar studies were conducted for the lithological and facies dissection of ore deposits based on geological and well data to clarify the genesis of the formation of deposits and hydrocarbon sources within the Yablunivska structure of the Dnipro-Donetsk Basin by O.M. Karpenko *et al*. (2021). The authors used cluster and factor analyses, as well as the method of interpreting K. Passy's well log data, to quantify the organic carbon (OC) content in the rock. The results of the studies made it possible to establish certain regularities in the geological structure and identify lithological heterogeneities in the spatial distribution of sedimentary and facies rock lithotypes, as well as facies rock types, thickness of their radioactive layers and organic carbon content. Such studies should be complemented by laboratory core studies, which will allow for a deeper and more comprehensive assessment of the reservoir structure.

Such studies are informative for the needs of rapid analysis of poorly studied geological sections where the parameters are determined directly from the logging diagrams. The inclusion of information on petrophysical properties of reservoir rocks from selected core samples can provide reliable information on the potential productivity and characteristics of the reservoir rock, which will lead to an increase in the accuracy of their assessment. However, to assess the impact of the structure of lithological and stratigraphic sections and capacitance-filtration parameters on the readings of the logging results, new methods and techniques should be introduced to create reliable petrophysical models of complex thin-layer geological sections to improve the efficiency of their interpretation.

Conclusions

According to the results of the description of the polished sections, the porous rock is enriched with foraminifera remains and turns into a silty marl. The amount of foraminifera shells reaches 30-50%. Pyrites and brown organic matter are located around the foraminifera. The cementing substrate is sharply enriched with clay substance, in which glauconite is closely fused with pyrite. The fragments contain single particles of amber, staurolite, and zircon with black and brown borders, which indicates that the fragments were removed from the weathering crust of the neighbouring land of the platform, which was being eroded. Clay clots contain almost no foraminifera, but pyrite inclusions are present. Such features of the rock structure suggest that Neogene sediments were formed in the underwater part of the delta of the ancient river flow. They may be associated with rocks with good reservoir properties.

It has also been established that siltstones with quartz-clay cement consist of well-sorted quartz fragments 0.1-0.5 mm in size, which are in contact with each other. There are single inclusions of zircon and garnet, washed glauconite. Clay cement is localised in some pores and does not always completely fill them. About 5% of intergranular large pores are filled with rounded or amoebic calcite clots. The rock was formed in a coastal shallow water environment, which determines its good reservoir properties. Changes in the rock cement led to changes in its structure and deterioration of reservoir properties. Accordingly, the productive intervals in Miocene sediments are filled with highly porous, medium-porous and low-porous reservoirs, which are characterised by significant facies, lithological and petrophysical changes that significantly affect the results of the well logging.

As a result of laboratory experimental studies of core material taken from Neogene sediments, a complex structure of reservoir rocks was established, taking into account the influence of tectonic structure on the formation of sandstones, clays and siltstones. Based on the obtained parameters of porosity and permeability of productive reservoir rocks, the graphs of interrelationships and relative electrical resistivity with changes in reservoir pressure were constructed, in particular for polymict and monomict reservoir rocks. From the graphs established by the results of experimental studies, it is clear that for certain relative electrical resistivity ratios, pressure does not affect the change in the electrical conductivity of reservoir rocks. However, with an increase in reservoir pressure in the range from 20 to 60 MPa, the relative resistivity will increase as the dynamics of rock compaction increase. To exclude the influence of the resistivity of the free fluid on the porosity parameters, the derived formula (4) can be used. The task of further research is to test the results in neighbouring fields, the geological section of which is represented by similar rocks. Also, in the future, it is necessary to develop consolidated petrophysical models for this type of reservoir rocks and improve them.

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Conflict of Interest

None.

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Оцінка впливу будови літолого-стратиграфічних розрізів та ємнісно-фільтраційних параметрів на покази результатів геофізичних досліджень свердловин

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Анотація. Підвищення видобутку вуглеводнів із порід-колекторів складної будови, в межах неогенової системи Більче-Волицької зони Передкарпатського прогину, є доволі багатогранною проблемою, яку необхідно обґрунтувати шляхом проведення комплексних геофізичних, петрофізичних та петрографічних досліджень. Метою було обґрунтувати фізико-механічні, електричні, акустичні та петрофізичні параметри за результатами геофізичних досліджень у тонкошаруватому неогеновому розрізі газових та газоконденсатних родовищ у межах Більче-Волицької зони Передкарпатського прогину. Методика вивчення складнопобудованих неогенових відкладів у межах Більче-Волицької зони Передкарпатського прогину базувалася на якості результатів геофізичних та петрофізичних досліджень, отриманих безпосередньо в процесі буріння пошукових і розвідувальних свердловин. Окрім цього домінуючу роль відігравали результати лабораторних експериментальних досліджень взірців керну з відображенням пластових термобаричних умов. За результати таких комплексних геолого-геофізичних досліджень встановлено, що на покази геофізичних методів суттєво впливає тонкошарувата будова геологічного розрізу, що літологічно представлена перешаруванням пісковиків, алевролітів та аргілітів. З’ясовано, що значний вплив на покази геофізичних методів мають свердловинні прилади, які використовуються у геофізичних експедиціях. Результати досліджень спрямовані на підвищення ефективності пошуків вуглеводнів та контролю їхнього вилучення, тому наявність високо інформаційних комплексних геофізичних досліджень, зокрема багатозондового акустичного каротажу, високочастотного індукційного каротажного ізопараметричного зондування та повторного нейтронного каротажу дозволяє оптимізувати висновки на предмет перспективності виявлення вуглеводнів у складнопобудованих тонкошаруватих розрізах. Впровадження нових підходів до виділення таких пластів та прошарків дозволить підвищити інформативність геолого-геофізичних методів та приріст вуглеводнів у межах пошукових площ Більче-Волицької зони Передкарпатського прогину

Ключові слова: літотипи; колектора; коефіцієнти пористості та проникності; електричний опір; пори; акустичний імпеданс; електричні та акустичні зонди