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https://doi.org/10.26565/2410-7360-2024-61-01
UDC 550.832.5
Received 24 July 2024
Accepted 2 November 2024

Determination of shaliness parameters of terrigenous rocks in cased boreholes and while drilling by radioactive logging combination

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ABSTRACT

Introduction. Shaliness is an important lithological and petrophysical characteristic of reservoirs and seals in section of oil-and-gas boreholes as well as near-surface rocks (grounds) as the basis of buildings and engineering structures. Granulometric shaliness, determined by the presence of pelitic particles, and mineral shaliness, which characterizes the content of clay minerals, are distinguished in terrigenous rocks. In the sections of oil-and-gas fields, granulometric shaliness is one of the criteria for identifying reservoirs and affects their reservoir properties. The physical properties of reservoirs, which are studied by borehole logging, depend on the content and type of clay minerals. Information about clay minerals is taken into account when drilling and stimulation of hydrocarbon production. Shaly grounds apply to the group of cohesive ones, which in construction most often serve as the foundations of structures. At that these grounds are classified as difficult engineering-geological conditions for construction, since clay minerals specifically affect their strength, stability, etc. In oil-and-gas and engineering-geological boreholes the empirical equations relating gamma-ray logging readings and granulometric shaliness are most often used for quantitative estimation. Herewith, it is traditionally thought that the clay minerals make up the bulk of the pelitic particles.

The paper is concerned with increasing the informativity of the borehole logging while investigating the shaliness of terrigenous oil-and-gas reservoirs and near-surface rocks based on a combination of gamma-ray logging, gamma-gamma density logging and neutron-neutron logging (GR+DL+NL).

The investigation methodology included: borehole geophysical measurements by tools created at the Institute of Geophysics of the National Academy of Sciences of Ukraine independently and in collaboration with partner organizations; interpretation and analysis of logging data; justification and development of approaches to increase the informativity of the GR+DL+NL combination; estimation of the effectiveness of author's developments using independent criterions.

As a result of the investigation, on the basis of the abovementioned logging combination, the set of determined parameters is increased as compared with the traditional practice; number of new methods is developed for determining the parameters of shaliness, among them the content of clay minerals, their density and hydrogen index. The use of these parameters, in turn, improves the accuracy of porosity determination and other reservoir properties from logging data. Method for estimating the type of clay mineral according to the GR+DL+NL data is proposed. The method is an available alternative to geochemical core studies and to more expensive and difficult logging methods.

The novelty of the developments is confirmed by patents, and their effectiveness is confirmed by the results of borehole tests and comparison with independent determinations of parameters (laboratory core examinations, control logging data).

Practical significance. The proposed approaches are an important component of technologies for investigating oil-and-gas reservoirs and near-surface rocks, which are being developed at the Institute of Geophysics of the National Academy of Sciences of Ukraine.

***Keywords**: sand-shale rock; oil-and-gas reservoir; ground; combination of gamma-ray logging, gamma-gamma density logging and neutron-neutron logging; gamma-ray index; hydrogen index; density; clay mineral.*

In cites: Bondarenko Maksym, Kulyk Volodymyr. (2024). Determination of shaliness parameters of terrigenous rocks in cased boreholes and while drilling by radioactive logging combination. Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology", (61), 10-22. https://doi.org/10.26565/2410-7360-2024-61-01

Introduction

Terrigenous (sand-shale) rocks prevail among sedimentary rocks of both oil-and-gas fields and engineering-construction sites. Shaliness is an important lithological and petrophysical characteristic of this rocks [1–4].

Terminology. The term «shaliness» is ambiguous. In Soviet and post-Soviet special literature, granulometric and mineral shaliness, as well as insoluble residue (for carbonate deposits) are distinguished. *Granulometric shaliness* (or shale material) is determined by the presence of small pelitic particles in the rock (as is the convention, less than 0,01 mm) regardless of their mineral composition (mainly clay minerals, as well as quartz, feldspar, etc.). *Mineral shaliness* characterizes the content of clay minerals proper in the rock. The main among them are kaolinite, montmorillonite, chlorite and hydromicas [2, 5, 6].

In modern Western geological science, the term «*shale*» corresponds to granulometric shaliness, and «*clay*» corresponds to mineral shaliness. Log interpreters and petrophysicists often use these terms interchangeably as equivalent. This is explained by the common point about the predominance of clay minerals as a part of shale material, as well as the frequent lack of a priori data on percentage of clay in shale for a particular oil-gas field or section [7–9].

In the paper, we will use modern Western terminology [8].

Problem statement. Shale content is one of the factors in classing rocks into reservoirs and non-reservoirs for most terrigenous sections of oil-and-gas fields, as well as in classing reservoirs into layers with different reservoir properties (porosity, permeability, residual fluid saturation). Clay content, type and properties of clay minerals effect the physical properties of reservoirs (resistivity, radioactivity, elastic and neutron properties, etc.), which are investigated by geophysical borehole methods. Information about the mineral composition of shale material should be taken into account during drilling and procedures in the hydrocarbon production (in particular, shale gas). For example, montmorillonite is characterized by high swelling under the action of water, that must be taken into account when choosing a drilling mud. The plasticity of montmorillonite makes hydraulic fracturing (HF) difficult, and hydromica indicates rock brittleness, which favours HF. Kaolinite is a non-swelling mineral. It has the following features: the ability to relatively easily separate from quartz grains, be carried by the flow of hydrocarbons during their production, and to block pores, reducing permeability. Swelling is also not inherent in chlorite. However, this mineral loses iron under the action of acid treatment during the stimulation of production. That can lead to a loss of production rate due to the precipitation of a jellylike iron-bearing compound in the pores [2, 4, 8–12].

Shale material has a strong influence on the properties of the near-surface rocks (grounds) as the basis of engineering structures. Shale grounds and loess grounds are classified as difficult engineering-geological conditions for construction. Therefore, the investigation of shaliness is an important problem of engineering geology. At that, it is necessary to obtain information not only about the total content of shale material, but also about the clay minerals, which are contained in sand-shale grounds and specifically affect its strength and stability [3,13,14].

Single geophysical borehole methods are traditionally used to qualitatively and quantitatively estimating the rock shaliness in a well section: first of all, spontaneous potential and integral gamma-ray logging (GR). Their effectiveness is generally confirmed by long-term practice [5, 8, 15, 16]. At that, particularly gamma-ray logging application is usually limited to lithological layering and estimation of the shale content.

There are approaches for estimating clay content based on a combination of porosity determination methods: density gamma-gamma logging (DL), neutron-neutron logging (NL) and acoustic logging [17, 18].

Foreign companies use data from spectral gamma-ray logging, litho-density logging, pulsed neutron spectroscopy logging, etc. for estimating the type and content of specific clay minerals [8, 19–22]. However, the appropriate Western tools and techniques are expensive and not always adapted for use in specific conditions (logging while drilling, cased engineering-geological boreholes of small diameter, etc.).

Analysis of previous investigations

Parameters of mass and volume shaliness. There are appropriate mass and volume parameters to quantitatively characterize the content of shale material and content of clay minerals in a rock. These parameters are important in itself, they are used in the generation of petrophysical equations and interpretation of results of geophysical borehole investigation for determining rock properties.

In petrophysics, the *mass content of shale* C_{sh} is determined by the data of granulometric analysis of rock sample as the ratio of the mass of shale material m_{sh} to the mass of solid phase m_s of the rock sample [2]:

$$C_{sh} = \frac{m_{sh}}{m_s} . \qquad (1)$$

The part of the rock volume filled by shale material is characterized by the *volume content of shale* K_{sh} [2]:

$$K_{sh} = \frac{\delta_s}{\delta_{sh}} C_{sh} (1-\phi) . \qquad (2)$$

Here, ϕ is the total porosity of the rock as the sum of open and closed porosity; δ_s is the density of solid phase of rock; δ_{sh} is the density of shale.

Along with the shale parameters, there is a need to obtain the mass content of clay and volume content of clay directly.

The *mass content of clay* C_{cl} is ratio of the mass of clay minerals m_{cl} to the mass of solid phase m_s of the rock:

$$C_{cl} = \frac{m_{cl}}{m_s} . \qquad (3)$$

The value of C_{cl} can be estimated by laboratory methods based on X-ray diffraction analysis or researching the cation exchange capacity [7–10].

The volume content of clay K_{cl} is part of the rock volume filled by clay minerals [8]:

$$K_{cl} = \frac{\delta_s}{\delta_{cl}} C_{cl}(1-\phi)\,. \qquad (4)$$

where δ_{cl} is density of clay minerals.

In order to determine the volume parameters K_{sh} and K_{cl}, in addition to the mass parameters C_{sh} and C_{cl}, it is necessary to know the density parameters δ_s, δ_{sh} and δ_{cl}, as well as the total porosity ϕ. Density and porosity parameters can be known from laboratory-based core analysis. Density parameters can be estimated from geophysical borehole logging (e.g., by the radioactive logging combination with using a priori data [23]), and porosity ϕ is determined from neutron-neutron logging or density gamma-gamma logging, as well as from acoustic logging.

In many cases, the density of clay minerals mixture δ_{cl} is close to the density of the matrix of sandstones [2] therefore simplified versions of formulas (2) and (4) can be used in practice:

$$K_{sh} = C_{sh}(1-\phi)\,, \qquad (5)$$

$$K_{cl} = C_{cl}(1-\phi)\,. \qquad (6)$$

Estimation of shale content by gamma-ray logging. The presence of shale material (and, accordingly, clay minerals) in the borehole section has effect on the readings of most logging methods. In order to corresponding quantitative estimate in borehole conditions, single logging methods are traditionally used, as well as combinations of methods [5, 7, 8, 16, 17, 24].

In practice, gamma-ray logging and the simplest empirical models are most often used to determine the shale content of terrigenous rocks [16]. Shale is characterized by increased radioactivity due to the large specific surface area of pelitic particles, that sorb salts of radioactive elements (mainly uranium-radium and thorium isotopes, as well as the ^{40}K isotope), and because of the presence of potassium in some clay minerals and in feldspar. This, in fact, makes it possible to distinguish rocks by shale content and quantifying it according to the GR data [5, 8].

In order to quantify the shale content of rocks C_{sh} in the section of oil-and-gas and engineering-geological boreholes, it is conventionally to employ the correlation between the C_{sh} parameter, which is determined in the laboratory, and the interpretive parameter of gamma-ray logging in the form of index ΔI_γ [5, 8, 14, 16]:

$$\Delta I_\gamma = f_1(C_{sh})\,. \qquad (7)$$

Index of gamma-ray logging ΔI_γ is determined as follows:

$$\Delta I_\gamma = \frac{I_\gamma - I_\gamma^{min}}{I_\gamma^{max} - I_\gamma^{min}}\,, \qquad (8)$$

where I_γ is readings of the GR detector along the borehole; I_γ^{min} and I_γ^{max} are the reference readings of the GR detector (commonly this values are determined in slightly radioactive bed and in shale bed with high gamma-ray activity, respectively) [5, 8, 9, 14–16, 24–26].

Petrophysicists have proposed a lot of variants of equations depicting the correlation between shale content and GR readings for specific fields or sediments of a certain type [16].

There are known Larionov's [27] dependences of GR index on mass content of shale C_{sh} in terrigenous rocks. These dependences are widely used in the territory of the former USSR and in other countries [6, 8, 16, 26, 28]. The generalized dependence for quartz sandstones [5] is shown in Fig. 1*a*, curve *1*:

$$\Delta I_\gamma = -1,28C_{sh}^2 + 2,28C_{sh}\,. \qquad (9)$$

This dependence is the graduation characteristic of the gamma-ray logging.

The corresponding calibration function of gamma-ray logging for determining the mass content of shale is shown in Fig. 1*b*, curve *1*:

$$C_{sh}^\gamma = 2,60\Delta I_\gamma^4 - 3,35\Delta I_\gamma^3 + 1,78\Delta I_\gamma^2 + 0,15\Delta I_\gamma\,. \qquad (10)$$

The purpose of the paper is increasing the informativity and improving the accuracy of logging in determining the parameters of shaliness and other parameters of rocks, which require information about shaliness. The emphasis in the study is on logging when there is a steel string (drill one or casing one) in the borehole.

Methods, materials, petrophysical model

At the Institute of Geophysics of the National Academy of Sciences of Ukraine (IGPh) has been created a number of new methods based on the combination of gamma-ray logging, density gamma-gamma logging and neutron-neutron logging (GR+DL+NL) for determining parameters of shaliness [23, 29, 30]. These developments allow to increase the number of determined rock parameters and achieve the purpose of investigation. Above-noted radioactive logging methods are universal in regard to borehole conditions (logging-while-drilling, logging in open and cased oil-and-gas boreholes, logging in near-surface engineering-geological boreholes, etc.). The methods are successfully used in practice and are traditional to well-log analysts.

The paper uses the results of field works carried out in cooperation with partner organizations at oil-and-gas and methane-coal fields, at engineering-geological sites (SOE «Enerhoproekt», LLC «Ukrspetsheolohiia», LLC «Ukrspetsprylad»). The measurements were performed with the help of tools, which created at the IGPh independently and in cooperation with partner organizations within the terms of scientific cooperation agreements. Laboratory data and control logging results, which have been provided by partner organizations, were used as an independent criterion for estimating efficiency of the author's developments.

We have taken into consideration the following

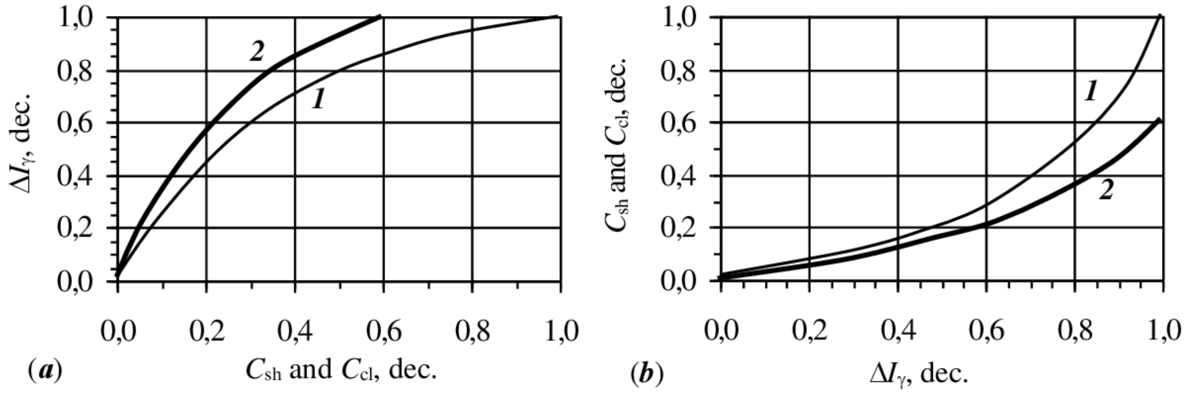

Fig. 1. Graduation characteristics (*a*) and calibration functions (*b*) of the gamma-ray logging
1 – mass content of shale C_{sh}; *2* – mass content of clay C_{cl}; dec. – decimal fraction

petrophysical model of terrigenous rock. The rock consists of a solid phase and pore space filled with fluid (water, oil) and gaseous phases in various proportions. The pores can be open, closed, or mixed. The solid phase of the rock consists of skeleton (quartz grains ~1,0 ÷ 0,01 mm in size) and shale material (particles smaller than 0,01 mm). Shale material includes clay minerals, fine quartz particles and other minerals (feldspars, carbonates, etc.). Clay minerals contain chemically bound water and are characterized by their chemical composition, density and hydrogen index.

Results and analysis

Determining clay content by gamma-ray logging. Log analysts have long noted that the usage of shale content based on traditional empirical models of type (7) often leads to inaccurate estimation of reservoir properties, in particular porosity based on neutron-neutron logging, acoustic logging, etc. The main mistake here is to assume that the shale material contains 100 % clay minerals [7, 9, 16]. Another disadvantage of this approach is the incorrectness of using the shale content to quantify the hydrogen index of clay minerals by the radioactive logging combination (GR+DL+NL) [30].

Core analysis using X-ray diffraction [31] showed that the relative mass of clay minerals C_{cl} is 50÷70 % of shale material, 25÷45 % are quartz particles and 5 % – other minerals. On a bounded interval of C_{cl} values, Bhuyan and Passey [7] established relationship between the parameters C_{cl} and ΔI_γ.

Taking into account the results of Bhuyan and Passey [7] and based on own experience in interpretation of GR data, we proposed (Fig. 1*a*, curve *2*) generalized graduation characteristic of GR for the content of clay minerals $\Delta I_\gamma = f_2(C_{cl})$, which in our case is described by the equation

$$\Delta I_\gamma = -2,52C_{cl}^2 + 3,18C_{cl}\,. \quad (11)$$

The corresponding calibration function of the GR for determining the mass content of clay minerals along the borehole section (Fig. 1*b*, curve *2*) is as follows [30]:

$$C_{cl}^{\gamma} = 0,74\Delta I_\gamma^4 - 0,84\Delta I_\gamma^3 + 0,51\Delta I_\gamma^2 + 0,20\Delta I_\gamma\,. \quad (12)$$

The obtained dependence allows to abandon the generally accepted assumption [2, 8] that the shale material contains predominantly of clay minerals, and therefore it was assumed that $C_{cl} \approx C_{sh}$. At the current level to solve practical problems, when a priori the percentage of clay minerals is unknown and it is not possible to establish the graduation characteristic $\Delta I_\gamma = f_2(C_{cl})$, the «predominant» content of C_{cl} can be expressed by the approximate relation $C_{cl} \approx 0,6C_{sh}$ (i.e., the part of clay minerals in the total mass of shale material is ~ 60 % wt.) [30].

Volume contents of shale and clay. GR+NL combination. To determine the volume content of shale K_{sh} (5), it is necessary to know the porosity of the rock ϕ, in addition to the parameter C_{sh}. According to Larionov [27], the parameter ϕ is determined using a combination of methods NL+GR (or neutron-gamma logging + GR). This porosity ϕ can be used in equation (5) to obtain K_{sh}. According to the NL+GR combination, the last is determined as

$$K_{sh}^{\gamma+n} = \frac{C_{sh}^{\gamma}(1-\phi^{n})}{1-\varpi_{sh}C_{sh}^{\gamma}}\,, \quad (13)$$

where ϕ^{n} is porosity by NL («neutron» porosity), associated with the total hydrogen content in the rock (in pore water, clay minerals, etc.); ϖ_{sh} – estimated, according to preliminary data, the value of the hydrogen index of the shale material.

The parameter K_{cl} is related to C_{cl} by relation (6), and the total porosity ϕ, using NL, is equal to

$$\phi = \phi^{\mathrm{n}} - \varpi_{\mathrm{cl}} K_{\mathrm{cl}}, \quad (14)$$

where ϖ_{cl} is hydrogen index of the clay minerals, which a priori specified on the basis of a generalization of independent studies [e.g., 5, 8].

Solving the system of equations (6) and (14) for K_{cl}, we obtain the volume content of clay minerals by the GR + NL combination:

$$K_{\mathrm{cl}}^{\gamma+\mathrm{n}} = \frac{C_{\mathrm{cl}}^{\gamma}(1-\phi^{\mathrm{n}})}{1-\varpi_{\mathrm{cl}} C_{\mathrm{cl}}^{\gamma}}. \quad (15)$$

Thus, according to (13) and (15), the volume content of shale and the volume content of clay minerals can be determined from GR and NL data with the corresponding a priori accepted values of the hydrogen index of shale material and clay minerals [30].

GR+DL combination. To quantify the hydrogen indices of shale material and clay minerals in formulas (13) and (15), the traditional approach involves core sampling, laborious and expensive laboratory tests. At the same time, the problem of obtaining the parameters K_{sh} and K_{cl} without using predetermined values of ϖ_{sh} and ϖ_{cl} is solved using purely radioactive methods. To do this, in formulas (5) and (6) we use the mass parameters C_{sh}^{γ} and C_{cl}^{γ} by the GR and porosity by the density logging ϕ^{d}.

The total water-saturated porosity by the DL is determined as

$$\phi = \phi^{\mathrm{d}} = \frac{\delta_{\mathrm{s}} - \delta^{\mathrm{d}}}{\delta_{\mathrm{s}} - \delta_{\mathrm{w}}}, \quad (16)$$

where δ_{s} is the density of the solid phase of the rock (quartz skeleton together with shale material); δ_{w} – density of water in pore space; δ^{d} – density of rock along the borehole, determined by the calibration function of the DL tool. Approximate values of parameters δ_{s} and δ_{w} for sand-shale rocks can be considered a priori given [5].

Substituting $\phi = \phi^{\mathrm{d}}$ into equations (5) and (6), we obtain the desired value of the parameters K_{sh} and K_{cl}:

$$K_{\mathrm{sh}}^{\gamma+\mathrm{d}} = C_{\mathrm{sh}}(1-\phi^{\mathrm{d}}), \quad (17)$$

$$K_{\mathrm{cl}}^{\gamma+\mathrm{d}} = C_{\mathrm{cl}}(1-\phi^{\mathrm{d}}). \quad (18)$$

Thus, according to expressions (17) and (18), the volume contents of shale material and clay minerals, $K_{\mathrm{sh}}^{\gamma+\mathrm{d}}$ і $K_{\mathrm{cl}}^{\gamma+\mathrm{d}}$, are determined by the GR+DL data.

Hydrogen index of clay minerals and shale material. The hydrogen index of clay minerals ω_{cl} along a particular borehole section has independent significance, since together with the density of clay minerals makes it possible to identify the presence of specific clay minerals. The parameter ω_{cl} of water-saturated rocks can be determined from the results of GR+DL+NL combination.

The problem is solved by equating to the porosity on the basis of NL (Eq. 14) and the porosity on the basis of DL (Eq. 16). Let's solve the resulting equation for the parameter ω_{cl}, using expression (18) for the parameter K_{cl}. As a result, we get

$$\omega_{\mathrm{cl}}^{\gamma+\mathrm{d}+\mathrm{n}} = \frac{\phi^{\mathrm{n}} - \phi^{\mathrm{d}}}{C_{\mathrm{cl}}^{\gamma}(1-\phi^{\mathrm{d}})}. \quad (19)$$

The difference between ϕ^{n} («neutron» porosity by NL) and ϕ^{d} («true» porosity by DL), $\Delta_{\mathrm{ch.b.w.}} = \phi^{\mathrm{n}} - \phi^{\mathrm{d}} = \omega_{\mathrm{cl}} K_{\mathrm{cl}}$, has the meaning of apparent porosity due to chemically bound water in clay minerals.

Thus, according to Eq. (19), the hydrogen index of clay minerals along the borehole section can be determined by the GR+DL+NL combination [30].

The averaged value $\omega_{\mathrm{cl}}^{\gamma+\mathrm{d}+\mathrm{n}}$ (over selected layers or over borehole section) can be used in Eq. (15) when determining the parameter $K_{\mathrm{cl}}^{\gamma+\mathrm{n}}$ by GR+ NL.

When determining the volume shale content using Eq. (13), there are difficulties in choosing a specific value of the hydrogen index of the shale material ω_{sh}. At the same time, the parameter ω_{cl}, associated with ω_{sh}, is determined by the GR+DL+NL combination (Eq. 19). Using the relationships $C_{\mathrm{sh}}\omega_{\mathrm{sh}} = C_{\mathrm{cl}}\omega_{\mathrm{cl}}$ and $C_{\mathrm{cl}} \approx 0{,}6 C_{\mathrm{sh}}$, we obtain an approximate value of the hydrogen index of the shale material:

$$\omega_{\mathrm{sh}}^{\gamma+\mathrm{d}+\mathrm{n}} \approx 0{,}6\,\omega_{\mathrm{cl}}^{\gamma+\mathrm{d}+\mathrm{n}}. \quad (20)$$

If necessary, hydrogen index of shale material can be averaged layer-by-layer or along the investigated borehole section.

Thus, according to Eq. (20), the hydrogen index of the shale material can be determined from the GR+DL+NL combination [30].

Density of clay minerals. The density of the solid phase at full water saturation of the pores can be calculated using parameters, which are obtained by the radioactive logging combination (DL, NL, GR) [32], according to the equation:

$$\delta_{\mathrm{s}}^{\mathrm{d}+\mathrm{n}+\gamma} = \frac{\delta^{\mathrm{d}} - \delta_{\mathrm{w}}\phi^{\mathrm{n}+\gamma}}{1-\phi^{\mathrm{n}+\gamma}}, \quad (21)$$

where $\delta_s^{d+n+\gamma}$ is the density of the solid phase of the rock by DL+NL+GR; δ^d – total rock density according to the DL; δ_w is the density of water, which is given a priori (for example, for fresh water 1,00 g/cm^3); $\phi^{n+\gamma}$ – total porosity by the NL+GR combination using the calibration function of the NL tool for water-filled rocks under given measurement conditions and the relative content of clay minerals according to GR data.

In addition to the density of the solid phase, according to the proposed method [23], it is possible to determine the density of clay minerals and the density of shale material from the same radioactive combination (DL, NL, GR) together with a priori given constants.

According to the accepted petrophysical model, we use the relationship between the density of the solid phase δ_s of the sand-shale rock and the density of its components – clay minerals δ_{cl} and skeletal quartz grains together with quartz particles of shale material δ_q:

$$\delta_s = C_{cl}\delta_{cl} + C_q\delta_q , \qquad (22)$$

where C_{cl} is relative mass content of clay minerals in the solid phase;
$C_q = (1 - C_{cl})$ is relative mass content of quartz in the solid phase.

In compliance with Eq. (22), the desired density of clay minerals is equal to:

$$\delta_{cl} = \frac{\delta_s - C_q\delta_q}{C_{cl}} . \qquad (23)$$

Using Eq. (21) for density δ_s, we can rewrite Eq. (23) for the density of clay minerals as:

$$\delta_{cl}^{\gamma+d+n} = \frac{1}{C_{cl}^{\gamma}}\left[\frac{\delta^d - \phi^{n+\gamma}\delta_w}{1-\phi^{n+\gamma}} - (1 - C_{cl}^{\gamma})\delta_q\right], \qquad (24)$$

where δ_{cl} is the desired density of clay minerals; C_{cl}^{γ} is relative mass content of clay minerals in the solid phase of the rock, determined with the help of GR; δ_w and δ_q are a priori constants (densities of water and quartz, respectively) $\phi^{n+\gamma}$ is total porosity by the NL+GR combination; δ^d is total rock density according to the DL.

Suchwise, the density of clay minerals in the water-filled rocks according to the proposed method [23] is determined by calculation using Eq. (24) with the help of values directly measured by the radioactive logging combination (GR+DL+NL) and a priori specified constants.

The density of the shale material can be obtained in a similar way.

Estimation of clay mineral type. Determining the type of clay minerals in rock is actually a task of geochemistry [8]. An exact solution to this problem under borehole conditions can be obtained from the results of core examination. However, researchers have developed a number of logging techniques for estimating clay minerals, including using neural networks [8, 19–22].

We propose to estimate type of clay mineral with the help of the GR+DL+NL combination. The hydrogen index ω_{cl} (19) and density δ_{cl} (24) of clay minerals together characterize a specific mineral. By means of plotting a crossplot of the parameters ω_{cl} and δ_{cl}, which are determined by the above-mentioned logging combination, it is possible to identify a clay mineral in a water-filled rock (see Fig. 2). To apply the method in oil-filled rocks, a priori data on the density of oil (or fluid in the invasion zone) is required. The method does not apply to gas-saturated rocks, since in such rocks both the neutron porosity and density porosity are apparent porosities.

Fig. 2 illustrates the crossplot $\delta_{cl}\Leftrightarrow\omega_{cl}$ based on generalized measurement data in several engineering-geological boreholes for near-surface sand-shale rocks. The crossplot demonstrates the effectiveness of the proposed approach. Areas with a predominant content of a single mineral (montmorillonite, chlorite, hydromica) and a mix of minerals are identified on the crossplot.

Borehole examples of determination of shaliness parameters

Cased engineering-geological borehole. Fig. 3 gives an example of determining the shaliness parameters, density and total porosity of near-surface sand-shale rocks in the zone of full water saturation at the site of engineering-geological investigation. The site is located near the tailings dam of the Northern Mining and Processing Plant (Krivyi Rih). The logging was carried out using DL+GR and 2NL tools developed and made in the IGPh. Lithologically the borehole section is represented by grounds of varying degrees of shaliness (loam, shale, heavy shale). Control values of the parameters in Fig. 3 were obtained from laboratory petrophysical studies of rock samples taken along the borehole section. It can be seen that the logging determinations are in good agreement with independent laboratory data of shale and clay contents, total and solid phase densities, porosity.

For problems of oil-and-gas geophysics, given «cased borehole – near-surface rock» system acts as a full-scale model.

Logging-while-drilling of oil borehole. Determination of shaliness and other parameters according to logging-while-drilling (LWD) of deviated oil borehole (Dnipro-Donets depression (DDD), Poltava region) is shown in Fig. 4 for the terrigenous interval. The logging was carried out using the LWD-KPRK-48 tool, created by the IGPh and LLC "Ukrspetsprylad". The targeted operation reservoir

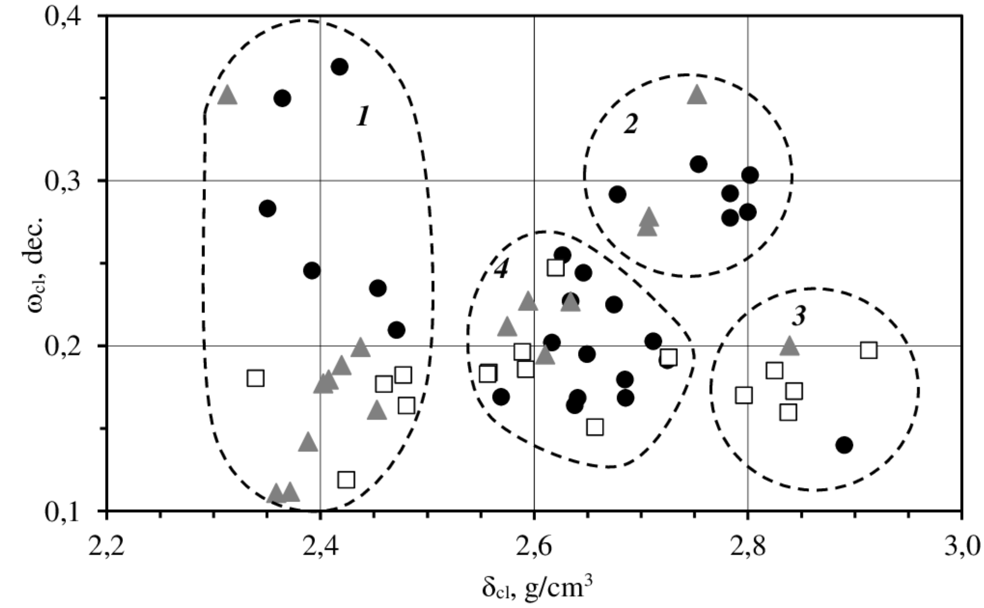

Fig. 2. Crossplot of density and hydrogen index for identification clay minerals
by an example of three engineering-geological boreholes (●, □, ▲).
Dotted line – area of predominant content of mineral: *1* – montmorillonites; *2* – chlorites,
3 – hydromicas; *4* – mix of minerals (~ 1/3 kaolinite + 1/3 hydromica + 1/3 montmorillonite)

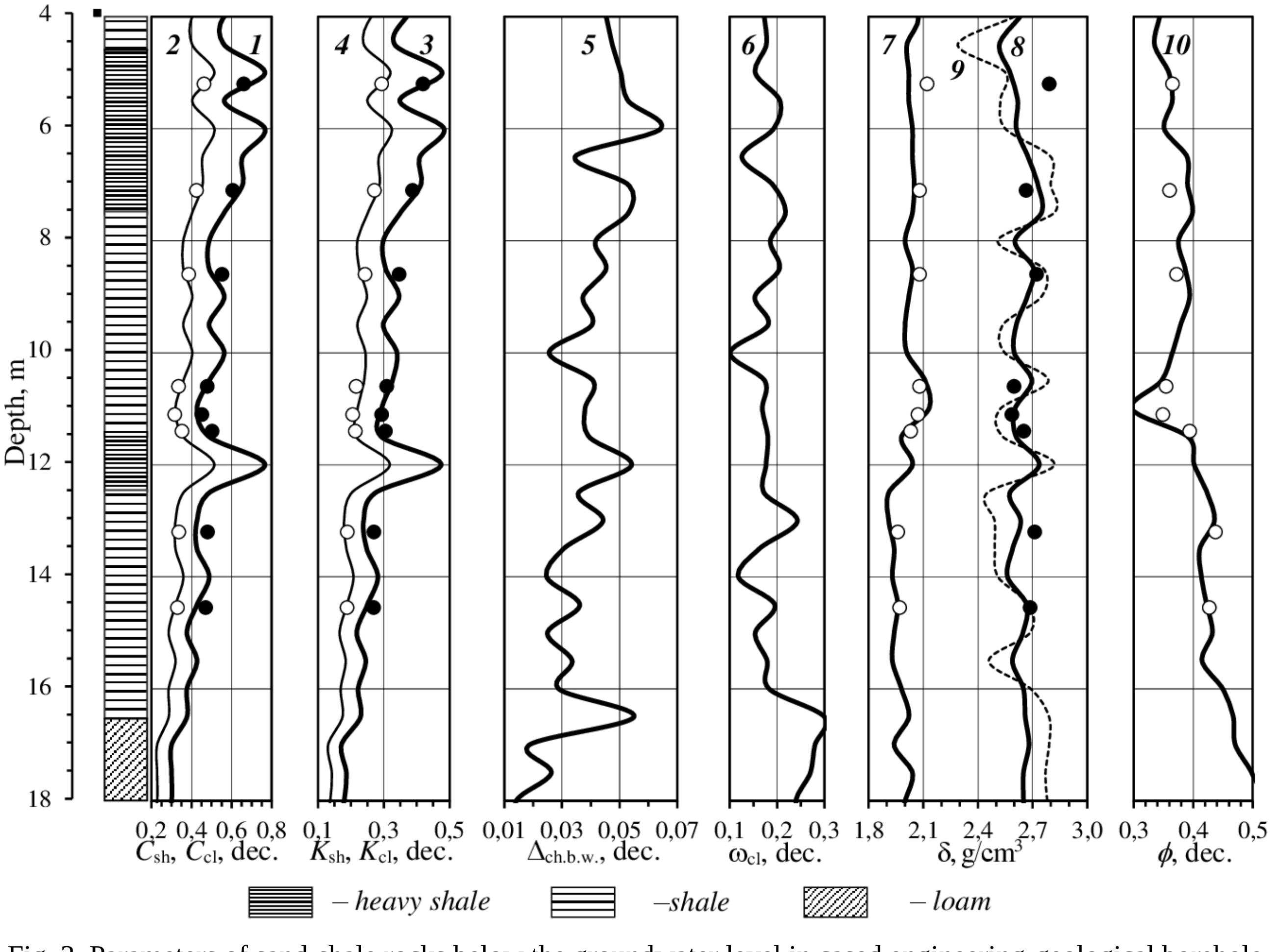

Fig. 3. Parameters of sand-shale rocks below the groundwater level in cased engineering-geological borehole
(Kryvyi Rih, borehole diam. d_b = 51 mm, casing diam. d_c = 51 mm).
Mass and volume shaliness: *1*, *3* – shale, *2*, *4* – clay, respectively; *5* – chemically bound water;
6 – hydrogen index of clay minerals; density: *7* – total, *8* – solid phase, *9* – clay minerals; *10* – total porosity.
○, ● – control laboratory data; dec. – decimal fraction

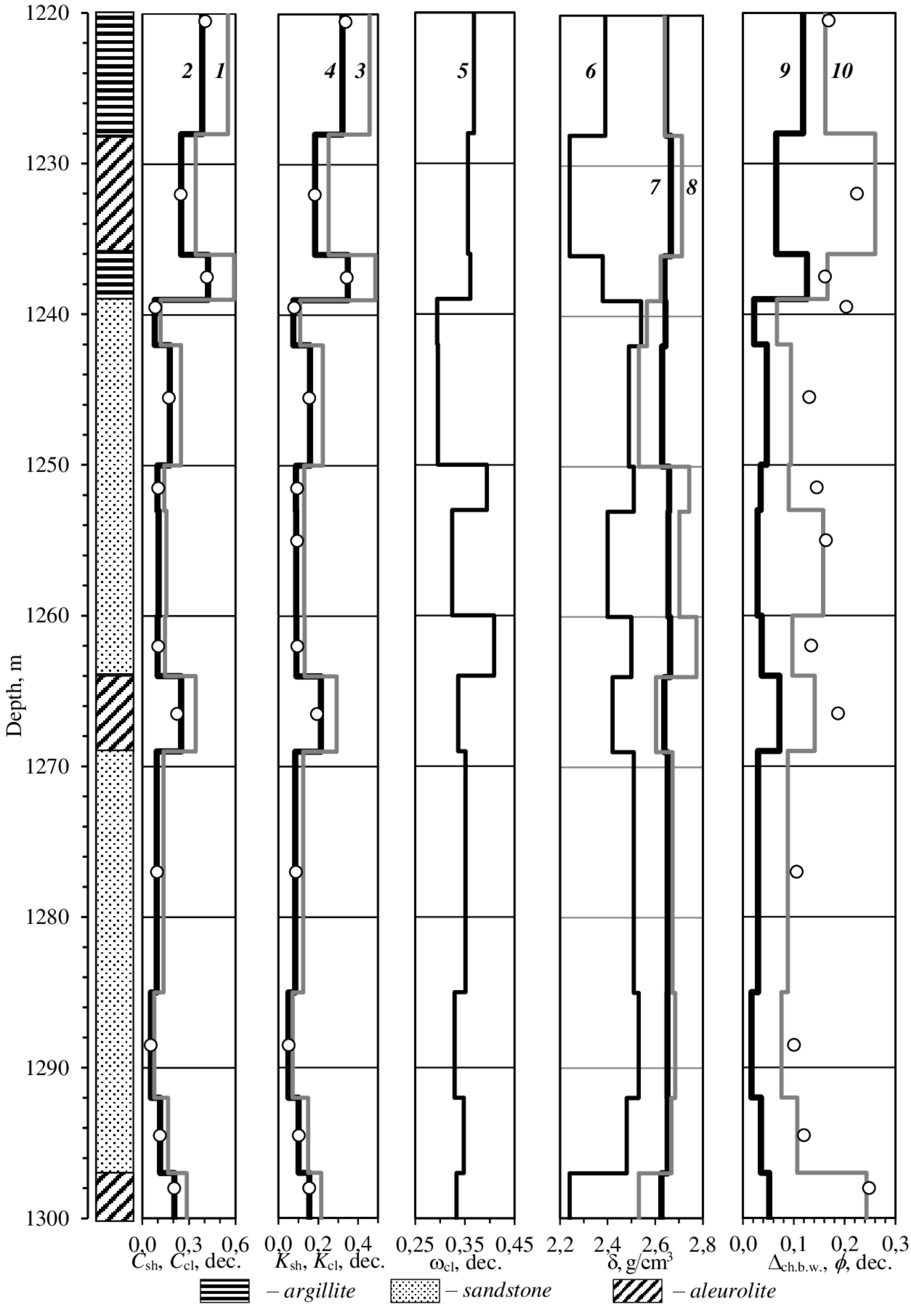

Fig. 4. Parameters of terrigenous rocks in deviated oil boreholeby logging-while-drilling using the LWD-KPRK-48 tool (Dnipro-Donets depression, d_b = 216 mm, drillstem diam. d_d = 132 mm). Mass and volume shaliness: *1*, *3* – shale, *2*, *4* – clay, respectively; *5* – hydrogen index of clay minerals; density: *6* – total, *7* – solid phase, *8* – clay minerals; *9* – chemically bound water; *10* – total porosity; ○ –control layer-by-layer logging data in the open hole

is represented by low-shale sandstone; argillites and aleurolites are also identified. The LWD results are in good agreement with the control logging (determination of clay content and porosity) performed in the open hole after drilling.

Cased methane-coal borehole. Fig. 5 shows an example of determination of the shaliness and others parameters in the cased methane-coal borehole (mine field «Samsonivska-Zakhidna», Luhansk region). The logging was carried out using 2DL-48 and 2NL-48 tools, developed and manufactured at the IGPh. Terrigenous rocks of different shaliness were identified: argillite, sandstone, aleurolite. A low-density coal bed and tight limestone have also been identified. Limestone is characterized by almost zero shaliness. To determination of the shaliness parameters of coal, it is necessary to develop special methods.

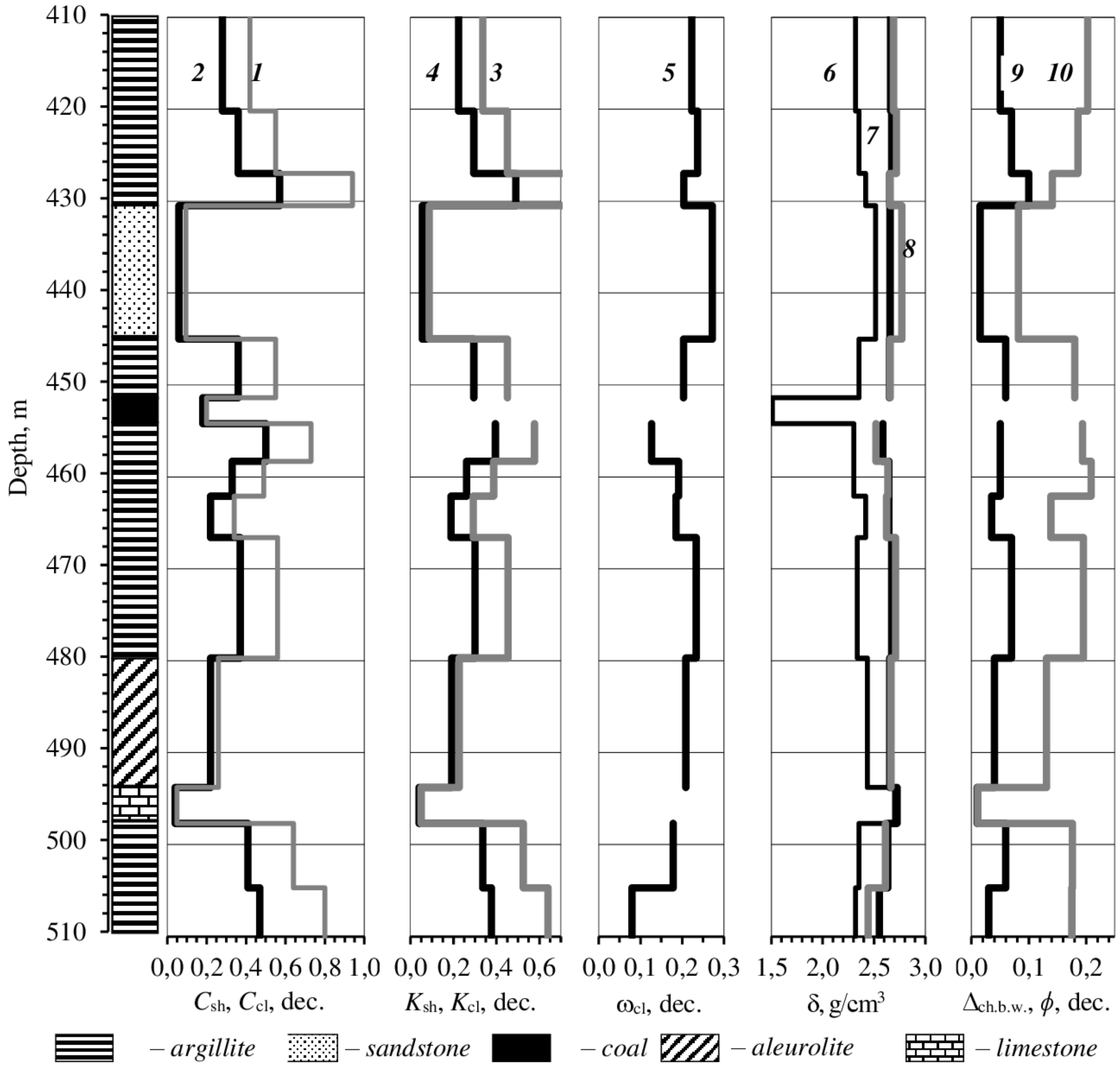

Fig. 5. Rock parameters in cased methane-coal borehole by 2DL-48 and 2NL-48 tools (Dnipro-Donets depression, d_b = 159 mm, d_c = 108 mm).
Mass and volume shaliness: *1*, *3* – shale, *2*, *4* – clay, respectively; *5* – hydrogen index of clay minerals; density: *6* – total, *7* – solid phase, *8* – clay minerals; *9* – chemically bound water; *10* – total porosity

Conclusions

Based on the GR+DL+NL combination, the informativity of well logging has been increased in determining the shaliness parameters of terrigenous oil-and-gas formations and near-surface rocks. At that, the emphasis is on investigations through a steel string (drill or casing).

1. A number of logging methods for determining shaliness parameters have been developed, patented and tested in practice. The proposed methods unveil additional capabilities of the GR+DL+NL combination and increase the set of determined pa-

rameters compared to the traditional approach. Determination of additional practical petrophysical parameters (content, density and hydrogen index of clay minerals) increases the accuracy of porosity and other reservoir parameters by well logging.

2. A method has been proposed for estimating the type of clay mineral based on the data of the same radioactive logging combination. This information is used in the interpretation of logging data and is important during drilling operations and stimulation of hydrocarbon production, as well as engineering-geological survey.

3. The efficiency of the developed methods is confirmed by the results of borehole tests and comparison with independent determinations of parameters (laboratory core studies, control logging data). The «price – quality – efficiency» ratio of the obtained results demonstrates the advantage of logging methods for determining shaliness parameters and other parameters compared to laboratory ones. The latters, of course, must be selectively used as a criterion of accuracy and validity.

4. The proposed approaches are an important component of the exploration technology for oil-and-gas reservoirs (in open and cased boreholes and while drilling) and the investigation technology for near-surface rocks, developed at the Institute of Geophysics of the National Academy of Sciences of Ukraine on the basis of a radioactive logging combination.

Acknowledgements

The authors are grateful to director of LLC «Ukrspetsheolohiia» O.S. Stasiv, director of LLC «Ukrspetsprylad» S.M. Danyliv and officials of SOE «Enerhoproekt» S.I. Deineko and S.O. Ivaschenko for organizing the borehole tests of the new developments.

Thanks are due to co-workers of the Institute of Geophysics of the NAS of Ukraine Z.M. Yevstakhevych, S.I. Diachenko, O.V. Dmytrenko for taking part in development of pilot samples of logging tools and carrying out radioactive logging.

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Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

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Визначення параметрів глинистості теригенних гірських порід в обсаджених свердловинах та в процесі буріння комплексом радіоактивного каротажу

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Глинистість є важливою літологічною і петрофізичною характеристикою колекторів і покришок в розрізі нафтогазових свердловин та приповерхневих гірських порід (ґрунтів) як основи інженерних споруд. В теригенних породах розрізняють гранулометричну глинистість, яка визначається наявністю пелітових частинок, та мінеральну глинистість, яка характеризує вміст глинистих мінералів. В розрізах нафтогазових родовищ гранулометрична глинистість є одним з критеріїв при виділенні колекторів та впливає на їхні фільтраційно-ємнісні властивості (ФЄВ). Фізичні властивості колекторів, які вивчають геофізичними свердловинними методами (ГСД), залежать від вмісту і типу глинистих мінералів. Інформацію про глинисті мінерали враховують при бурінні та інтенсифікації видобування вуглеводнів. Глинисті ґрунти належать до групи зв'язних, які у будівництві найбільш часто служать основами споруд. При цьому такі ґрунти відносять до складних інженерно-геологічних умов будівництва, оскільки глинисті мінерали специфічно впливають на їхню міцність, стійкість та ін. Метою статті є розширення інформативності ГСД при дослідженні глинистості теригенних нафтогазових колекторів і приповерхневих гірських порід на основі комплексу гамма-, гамма-гамма і нейтрон-нейтронного каротажу (ГК+ГГК+ННК). Методика досліджень включала ГСД приладами, створеними в Інституті геофізики ім. С.І. Субботіна НАН України (ІГФ НАНУ) самостійно і у співробітництві з організаціями-партнерами, інтерпретацію каротажних матеріалів, розроблення підходів для підвищення інформативності ГК+ГГК+ННК, оцінку ефективності авторських розробок з використанням незалежних критеріїв. В результаті дослідження розширено (на основі комплексу ГК+ГГК+ННК) сукупність визначуваних параметрів гірських порід порівняно з традиційною практикою; розроблено ряд нових способів визначення параметрів глинистості, зокрема вмісту, густини і водневого індексу глинистих мінералів. Використання цих параметрів, в свою чергу, підвищує точність визначення пористості та ін. ФЄВ за даними ГСД. Запропоновано спосіб оцінки типу глинистого мінералу за даними ГК+ГГК+ННК. Спосіб є доступною альтернативою геохімічним дослідженням керну та більш дорогим і складним каротажним способам. Новизна розробок підтверджена патентами, а ефективність – свердловинними випробуваннями та порівнянням з незалежними визначеннями параметрів. Запропоновані підходи є складовою технологій дослідження нафтогазових колекторів та приповерхневих гірських порід, які розробляються в ІГФ НАНУ.

Ключові слова*: піщано-глиниста гірська порода; нафтогазовий колектор; ґрунт; комплекс гамма-, гамма-гамма і нейтрон-нейтронного каротажу; відносний різницевий параметр гамма-каротажу; водневий індекс; густина; глинистий мінерал.*

Внесок авторів: всі автори зробили рівний внесок у цю роботу

Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Надійшла 24 липня 2024 р.
Прийнята 2 листопада 2024 р.