

CHALLENGES IN DETERMINING CLAY CONTENT AND POROSITY OF CLAY RESERVOIRS USING NUCLEAR PHYSICS METHODS

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Abstract

The study examines the key factors influencing the intensity of secondary gamma radiation and the gamma activity of geological formations. It is found that the quantitative assessment of the pelitic fraction content is significantly influenced by the mineral composition of both the rock framework and the clay cement, as well as the spatial distribution and concentration of naturally occurring radioactive elements within different lithological rock types and weight fractions. A comprehensive methodology and algorithm has been developed to improve the accuracy of clay content and porosity determination in clayey reservoirs based on nuclear physics methods. These methods involve analyzing variations in gamma ray intensity and their correlation with mineralogical and geochemical properties of the subsurface formations. The proposed approach has been rigorously tested on real geological data from several hydrocarbon fields in Azerbaijan. The validation process included a comparative analysis with conventional petrophysical methods to assess the reliability and accuracy of the results. The effectiveness of the methodology is demonstrated through a practical case study, demonstrating its applicability in improving reservoir characterization and facilitating more informed decision making in hydrocarbon exploration and production.

Keywords: clayey reservoir, porosity, well, hydrogen content, clay content, radioactivity, natural radioactive elements

I. Introduction

The targeted application of a set of nuclear physics methods (NPM) in long-term developed fields enables the acquisition of essential data on the current characteristics of reservoir systems, the identification of additional reserves for enhanced oil recovery, and the establishment of a modern information framework for effective reservoir management. At present, there is no viable alternative to nuclear physics methods for solving these challenges in cased wells.

Among geophysical well-logging methods (GWL) used to determine the reservoir's capacity and filtration properties, gamma logging (GL) and neutron gamma logging (NGL) are considered the most effective. However, quantitative interpretation in cased wells becomes even more complicated due to the influence of various factors on NPM readings, particularly NGL, such as variations in casing eccentricity along the borehole. This effect is especially pronounced in wells with large diameters and in formations with low hydrogen content, such as low-porosity or gas-bearing intervals. Consequently, the ability of NGL to provide reliable quantitative data on porosity in low-porosity reservoirs and gas saturation in cased wells is significantly limited.

On the other hand, NGL is employed (including as part of GWL) not only for porosity determination but also for monitoring changes in oil and gas saturation coefficients of reservoirs and for addressing other reservoir evaluation challenges [4]. The expansion of the range of problems

addressed through NPM is driven by the ability to derive a greater number of informative parameters from radioactive fields, many of which can be reliably determined only using modern mathematical methods. However, with large data volumes, processing NGL results, especially under complex geological and technical conditions, becomes a labor-intensive task.

Efforts to improve NGL methodology and interpretation have been focused on overcoming these limitations and addressing several other challenges.

II. Theoretical and Methodological Aspects

Clayey oil and gas reservoirs are complex natural systems composed of rock-forming and accessory minerals, organic matter (OM), and pore fluids. The reservoir potential and other properties of these rocks are shaped by geochemical interactions among their constituent components during lithogenesis. The extent of this interaction is determined by the textural characteristics of the rocks [1].

It is important to emphasize that the pore space of rocks is an integral element of their texture and evolves in tandem with changes in textural features. These features dictate the spatial arrangement and orientation of the rock components, thereby influencing reservoir properties.

The textural characteristics of rocks are closely linked to their material composition. The foundation of rock textures—and consequently, the pore system of clayey reservoirs—is established during sedimentogenesis and remains largely preserved through diagenesis and catagenesis.

Determination of clay content

In the study of petroleum source shales, the ability of gamma methods (GM) to assess the type of clay minerals and the overall clay content is of particular interest. In some cases, clay content is understood as granulometric clay content (pelitic fraction), independent of mineral composition, since this characteristic is crucial for evaluating the filtration properties of rocks. In other cases, structural clay content is considered, referring to the proportion of clay minerals containing chemically bound water, which influences the readings of acoustic logging (AL), neutron logging (NL), and pulsed gamma-gamma logging (PGGL).

It is well known [7] that the presence of clay minerals in sedimentary rocks, particularly those with high dispersion and bound water content, significantly affects many physical properties of rocks. As a result, the quantitative assessment of the degree of clay enrichment in sedimentary formations has become highly relevant, as this parameter is widely used in petroleum geology and geophysics.

Interest in evaluating clay content based on gamma spectrometry data remains strong. The analysis of radioactive element distribution across granulometric fractions has shown that thorium and potassium are predominantly associated with the pelitic and fine silt fractions, while uranium is mainly concentrated in the fine silt fraction with grain sizes of 0.01–0.05 mm. The variability of the mineral composition of clay cement across different stratigraphic sections and petroleum-bearing regions necessitates the search for relationships of the form $REE = F(K_{\text{clay}})$ for specific stratigraphic intervals.

The content of accessory minerals in the heavy mineral fraction of reservoir rocks generally does not exceed 2%. The behavior of potassium is complex and can vary depending on the abundance of rock fragments, micas, feldspars, the ratio of potassium to sodium feldspar varieties, the degree of their transformation, as well as the composition and quantity of clay minerals present.

Determination of Porosity

It is known that the basis for determining the porosity of terrigenous rocks using neutron logging methods is the dependence of the porosity coefficient (K_p) on the hydrogen index (ω_{Σ}), the tightness of which is regulated by variations in the values of the hydrogen content of the solid phase.

As an example, in the figure 1 shows a comparison of the equivalent moisture content and porosity of the formation rocks of the horizon VI of the PS.

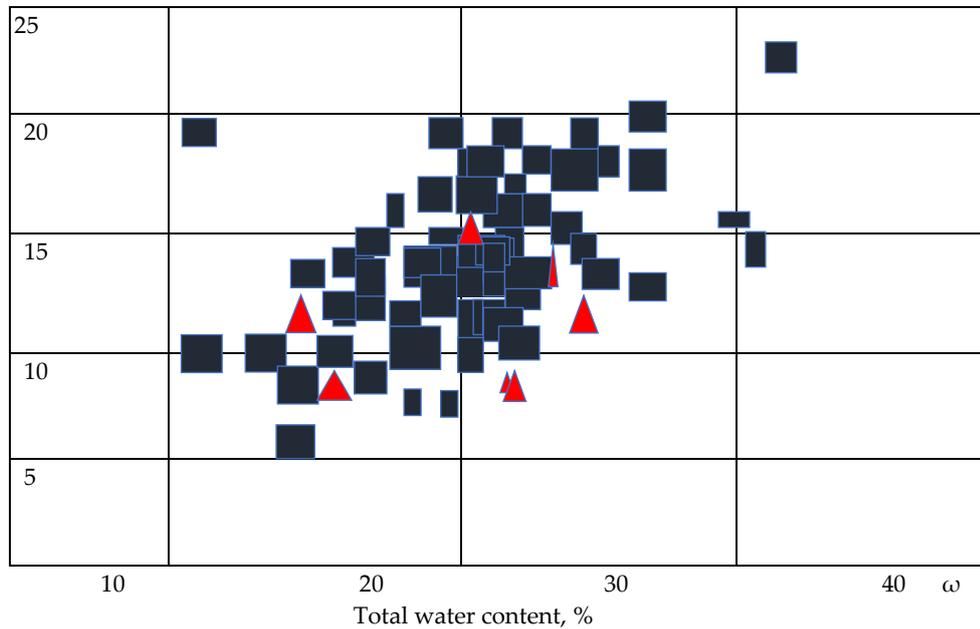


Fig. 1: Comparison of the total hydrogen content and the porosity coefficient of the rocks of the VI horizon of the Garabaghli field

■ - sandstones ▲ - aleurolites

The Garabaghli structure that oil-gas field confined is located 16 km south of the city of Shirvan, on the left bank of the Kura River, between the Kurovdag and Babazanan anticlines. The field area consists of a plain located 15-23 m below sea level (Fig.2).

The shale content methods, so the method of spontaneous potential (SP) and natural radioactivity (GL) can help take into account the effect of solid phase hydrogen on the neutron gamma logging (NGL) readings. Of the two possible options listed, the gamma method is more universal due to its independence from many geological and technological factors - mineralization and chemical composition (mineralization and chemical composition of formation water and drilling mud, type of solution, cementing, pyritization, etc.) [7, 10].

When studying clayey terrigenous reservoirs, simply increasing the sensitivity of neutron logging to changes in hydrogen content is insufficient. It is also necessary to determine the clay content, as the total hydrogen content of a clayey reservoir (ω_{Σ}), measured using neutron logging, consists of both the open porosity (K_p) and the crystallization water of the clay material (ω_c^{cr}), expressed as:

$$\omega_{\Sigma} = K_p + \omega_c^{cr}.$$

In formations where the radioactivity of the rock framework (i_{fw}) and the clay material (i_c) remains relatively constant, clay content—and consequently, the amount of crystallization water—can be determined from gamma logging (GL). However, in cases where the radioactivity of the clay material and the rock framework are comparable (i_c exceeding i_{fw} by no more than 3–4 times), the clay content estimated from GL is significantly influenced by the type of clay material and the reservoir structure.

To account for the effect of different clay types on gamma and neutron logging responses, it is useful to distinguish between dispersed clay content (C_{cc}) or clay cement and laminated or interspersed clay content (C_{cl}).

- Dispersed clay primarily replaces the nearly non-radioactive fluid in the pore space.

- Laminated and interspersed clay replaces the non-clay rock, whose radioactivity may be substantial [2,4,5].

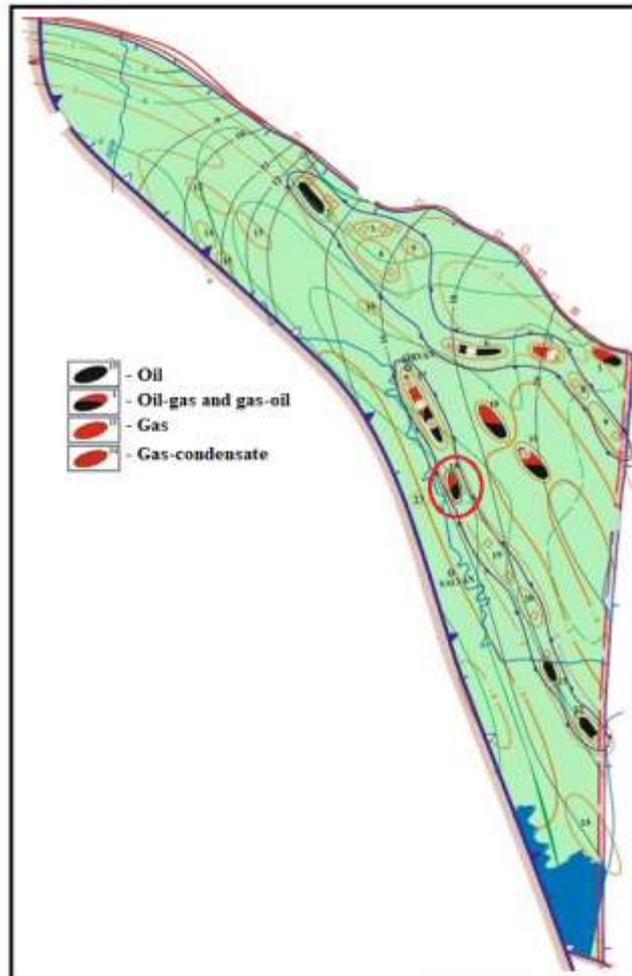


Fig. 2: Location map of the Garabaghli structure

In the latter case, the formation's radioactivity changes with increasing clay content by the difference in radioactivity between the clay and the non-clay rock.

Effect of clay type on hydrogen content

The variation in hydrogen content in a clayey formation also strongly depends on the type of clay material.

- Dispersed clay replaces water or oil with clay material, whose hydrogen content is at least twice as low as that of formation water or oil.

- Laminated or interspersed clay replaces rock, whose hydrogen content is typically close to or lower than that of the clay material.

Porosity Estimation in Clayey Reservoirs

Within a single hydrocarbon accumulation, the framework porosity of sand-clay reservoirs often varies within narrow limits and, within an acceptable margin of error, can be assumed to be constant. In this case, it is possible to determine the components of the clay material according to clay type (C_{cc} and C_{cl}) and, using the known framework porosity, calculate the open porosity of the reservoir using the equation:

$$K_p = [K_{p_{fw}} - C_{cc}(1 - K_{pc})] (1 - C_{cl}) + C_{cl} K_{pc}$$

where K_{pc} represents the porosity of the clay material.

III. Results and Discussion

Let's consider the petrophysical basis for using a complex methods of neutron logging and natural gamma field to determine the porosity and shale content of oil and gas saturated reservoirs.

The method of combining neutron and gamma logging is widely used in the combined interpretation of well logging data in productive formations of the Garabaghli field.

The above combination of methods is due to the dependence of the hydrogen content of the solid phase of rocks, on the one hand, and their natural gamma activity, on the other, on the content of shale material.

The object of this study is the Productive series (PS) of the Garabaghli structure, which represents the primary oil and gas-saturated interval within the geological section. This formation has been intersected by deep exploration and production wells drilled across various parts of the area (Fig.3). The maximum thickness of the PS, recorded in a well located on the southwestern limb of the fold, reaches 2,063 meters. The fold axis exhibits a weakly expressed S-shaped structure, trending from northeast to southwest, which shifts to a southeastern, then meridional, and further to a north-southwestern direction near the southeastern plunge.

The geological structure of the Garabaghli oil field includes Productive series deposits, as well as Aghjagil and Absheron stage formations, which are overlain by Gadim Khazar and modern deposits.

Productive series is the main oil- and gas-bearing horizon of the field section. It has been intersected by the deepest exploration and production wells located in various parts of the area. The upper 1000 m of thickness, corresponding to the first five PS horizons, are the most fully covered.

The maximum PS thickness encountered in a well on the southwestern limb of the structure is 2063 m. The drilled part of the section is characterized by alternating sand and clay layers. The base of the PS, opened in wells located in the uplifted part of the northeastern limb, corresponds to the XV horizon, beneath which Paleogene deposits composed of clays were encountered at a depth of 4250 m.

Horizon I, consists of alternating sand and clay layers. In most wells at the crest of the structure, a 20–25 m thick sand bed saturated with oil is distinguished, characterized by an electrical resistivity of 3–10 Ohm.

According to the geological interpretations Horizon I is completely eroded at the crest and in a significant part of both limbs. In this horizon, on the southwestern limb of the structure, transgressive deposits of the Aghjagil stage are present. The total thickness of Horizon I according to the composite section is 137 m.

Horizon II, compared to Horizon I, is more clay rich. At its top, there is a 20-meter thick sand bed characterized by an electrical resistivity of 4–7 Ohm. Below, a 30–40 m thick clay layer is distinguished, under which alternating sand-clay deposits with a thickness of about 100 m occur. This horizon is also eroded at the crest and in the uplifted parts of both flanks of the structure. The total thickness of the horizon according to the composite section is 107 m.

Horizon III is mainly encountered in wells on the southwestern limb and the southern pericline of the structure. The section begins with a sand bed characterized by an electrical resistivity of 3–7 Ohm. Further down the section, the number of clays interbeds gradually increases. This horizon is also eroded over a significant area, resulting in the transgressive deposition of Aghjagil deposits in its place within the near-crest zone, or their complete absence. The total thickness of Horizon III, according to the composite section, is 136 m.

Horizon IV consists of alternating sands, aleurites, and clays. Its upper part is sandier than its lower part. At the base of the horizon, a 20–25 m thick clay bed is present. The sand beds are characterized by an electrical resistivity of 4–7 Ohm. This horizon is also significantly eroded, leading to the transgressive deposition of Aghjagil deposits in the near-crest zone. The total thickness of Horizon IV, according to the composite section, is 152 m.

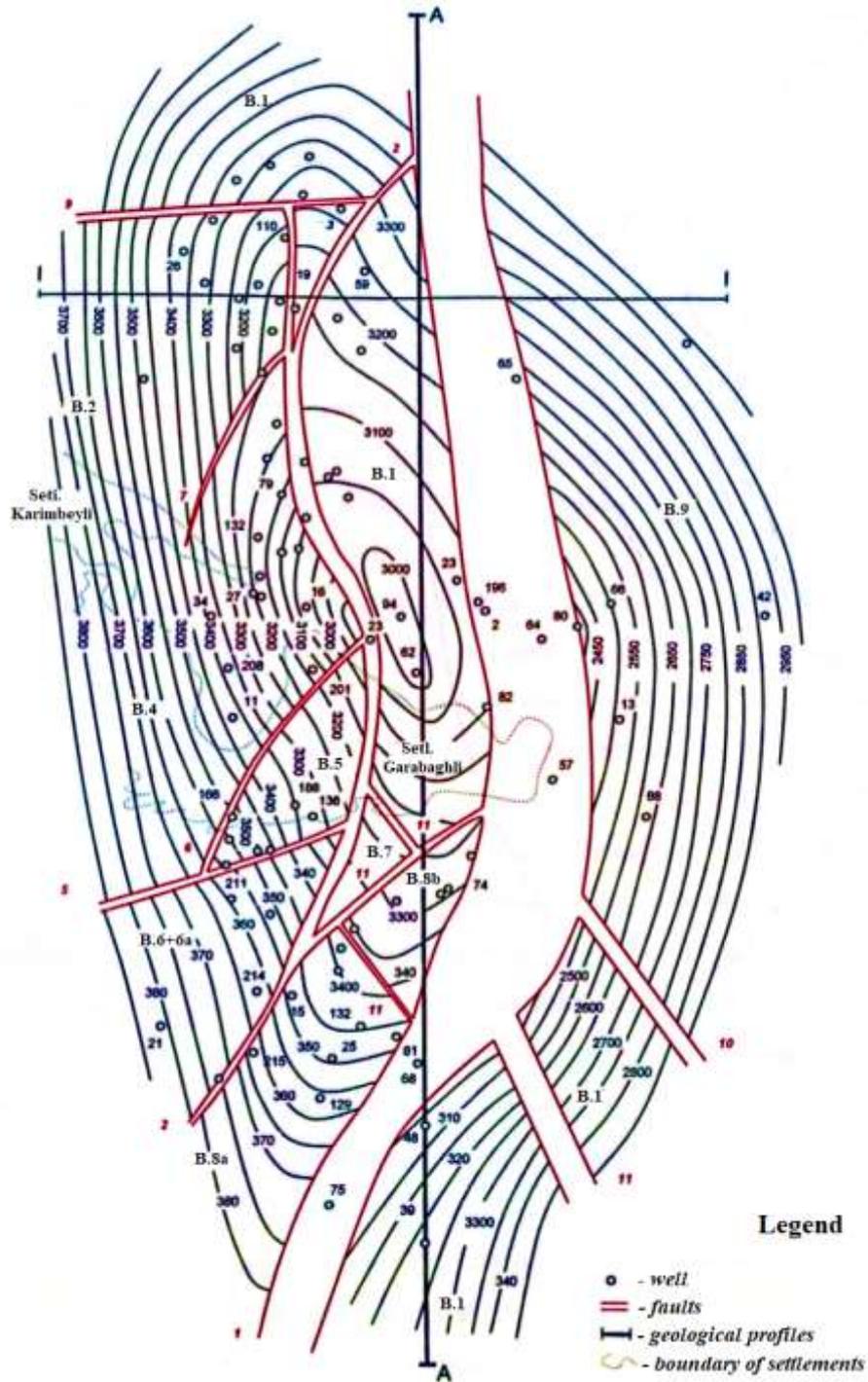


Fig.3: Structural map of Garabaghi oil field based on the top of Horizon VI

Horizon V is sandier than Horizon IV. At the top, it contains a 30–35 m thick sandy-clay bed. The middle part consists of alternating thin layers of sand and clay. The lower and middle sections are more clayey than the upper section. At the base, a 10–15 m thick clay layer is present, which is well-traced across the area. The sand layers are characterized by an electrical resistivity of 3–8 Ohm. Compared to the other (upper) horizons, this horizon is eroded over a small area, mainly within the crest of the structure. The total thickness of Horizon V, according to the composite section, is 206 m.

Horizon VI is sandier than Horizon V. The section begins with a 45–50 m thick sand bed, characterized by an electrical resistivity of 7–10 Ohm. In the middle part of the section, a 30–35 m

thick sand bed is separated from the overlying sandy layer by a 40 m thick clay interbed. The section terminates with a clay bed. The total thickness of Horizon VI, according to the composite section, is 206 m.

Horizon VII consists of alternating sand and individual clay layers, characterized by an electrical resistivity of 3–6 Ohm. The total thickness of the horizon, according to the composite section, is 126 m.

Horizons VIII–XI are represented by alternating sand and clay interbeds. The total thickness of individual horizons varies between 90–194 m.

Horizon XII begins with highly clayey formations. The middle part consists of a conglomeratic bed with a thickness of 80 m, while the lower part is composed of high clay layers. The total thickness of the horizon, according to the composite section, is 225 m.

Horizon XIII begins with a sand-clay bed with a thickness of approximately 90 m. The sand layers are characterized by an electrical resistivity of 4–6 Ohm, while the lower part of the section is represented by clays. The total thickness of the horizon, according to the composite section, is 220 m.

Horizon XIV consists mainly of clay layers. Near the top, individual thin sand layers are encountered. The total thickness of the horizon, according to the composite section, is 190 m.

Horizon XV begins with a conglomeratic bed with a thickness of 40 m, characterized by an electrical resistivity of up to 30 Ohm. The lower part of the section is composed of clays. The total thickness of the horizon, according to the composite section, is 185 m.

Oil and gas accumulations across all productive horizons of the PS are predominantly concentrated in the southwestern limb of the fold, with partial saturation in the southeastern pericline. The highest hydrocarbon saturation is observed in the southeastern section of this limb (Fig.4).

The stratigraphic sequence of the studied interval is characterized by alternating sandy and clayey layers of varying thickness. The lower portion is composed predominantly of clay content. Within the reservoir, clay material is distributed as isolated aggregates of clay particles, interspersed with subcapillaries. The presence of chemically bound water and radioactive elements in clay minerals significantly influences radiometric logging measurements. Specifically:

- The presence of chemically bound water leads to a discrepancy between neutron logging porosity (NL) and total porosity.
- An increase in clay content within the rock correlates with a systematic increase in its radioactivity.

As clay content increases, the effective porosity, permeability, and reservoir capacity of the rock decrease correspondingly.

Thus, the clay content of the formation is one of the key factors determining whether a rock can function as a commercial reservoir. However, the clay fraction also significantly affects the physical properties of the rock and the petrophysical relationships that form the basis for geophysical logging (GL) interpretation. This necessitates the widespread application of well-logging methods for determining the clay parameters of productive reservoirs, using correlation relationships between the responses of various geophysical techniques and clay content parameters.

Reservoirs differ from host rocks in terms of permeability, porosity, and clay content, which serve as the basis for their identification using geophysical methods.

As mentioned earlier, the effectiveness of Neutron Gamma Logging (NGL) is influenced by various geological and technological factors, with a small number of key factors having the most significant impact on the measurement results. These factors can be quantified and assessed. To address the task at hand, methods for determining the porosity of reservoirs using NGL data have been developed.

The essence of these methods lies in determining a more accurate value for the relative intensity of the layers by sequentially considering these factors. Among the geological factors, clay content (C_d) was considered, as it governs the volume and structure of the pore space [6].

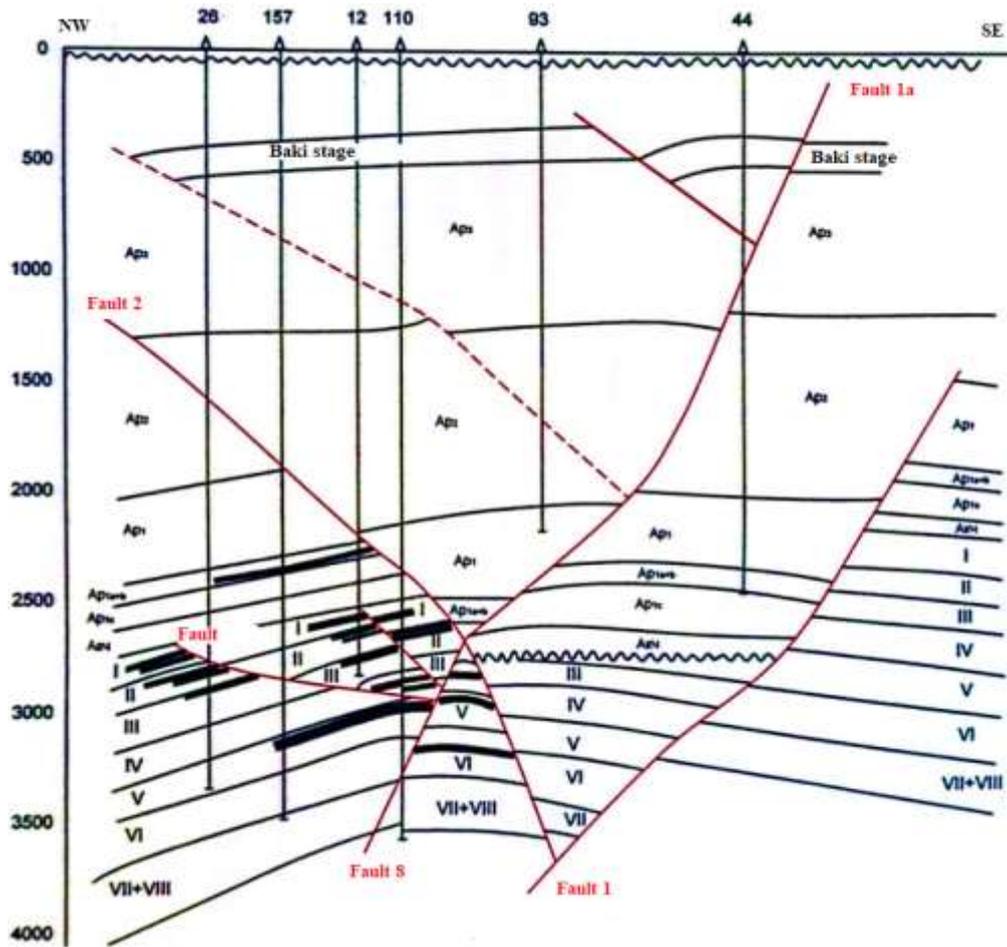


Fig.4: Latitudinal geological profile by the line I-I

Table 1: Results of Porosity Calculations (K_p) Using NGL, LL, and Core Data (Garabaghli structure)

Interval, m	H, m	GL, C_{cl} , %	K_p , %			K_{sat} , %	Lithology
			NGL	EL	core		
2598-2604	6	19	19.6	16.8	17	0.39	Sandstone
2606-2613	7	18	18.3	17.0	18.1	0.36	Sandstone
2623-2628	5	22	17.1	13.9	14.9	0.5	Sandstone
2632-2636	4	23	18	15.9	17.7	0.54	Sandstone
2636-2641	5	23	20.8	22.8	21.3	0.42	Sandstone
2681-2688	7	24	22.7	24.8	21.8	0.30	Sandstone
2743-2748	5	22	21.5	19.9	21.1	0.34	Sandstone
2750-2756	3	26	22.1	24.8	20.7	0.25	Sandstone
2785-2796	11	25	22.9	23.8	21.2	0.22	Sandstone
2842-2847	5	29	18	14	17.1	0.30	Sandstone
2849-2855	6	25	19.6	17	18.2	0.23	Sandstone
2857-2864	7	31	17.4	16.1	18	0.36	Clayey sandstone
2867-2889	22	29	18.2	14.6	16.9	0.30	Sandstone
2922-2929	7	30	20.4	19.6	18.7	0.22	Sandstone
2931-2938	7	33	19.2	22.0	17.9	0.25	Sandstone
2940-2947	7	26	19.5	16.9	18.1	0.25	Clayey sandstone
2970-2976	6	30	19.2	21.7	20.2	0.22	Sandstone

Clay content (C_{cl}) was calculated separately using Gamma Logging (GL) diagrams (see table 1). The methodology involved two reference layers. The formal and physical similarity of the equations for the average relative intensity of NGL and Lateral Logging (LL) facilitates the correlation of data from these two methods.

The reference layers were used, which is one of the most widely used universal methods. The porosity evaluation was performed using linear interpolation based on the known K_p values of two layers (a dense and a highly porous one) of the same age, which eliminated the distorting effects of various wellbore and geological factors that are typically difficult to account for by other methods.

The calculated porosity coefficients, using the refined corrections, were compared with the data from LL (Lateral Logging) and core analysis.

As seen from the table, the K_p values determined using NGL (Neutron Gamma Logging) show good agreement with the core data and LL results, confirming the validity of the proposed approaches.

Conclusions

As a result of the work conducted, the following conclusions were established:

- Clay content is a fundamental characteristic parameter for determining the main petrophysical properties of reservoir formations. The relationship between the clay content coefficients determined from the core and those calculated from the gamma-ray data is strong, with an approximation reliability coefficient (R^2) of 0.87.

- Moderate clay content in the reservoir does not have a significant impact on the K_p value.

- Various ways to introduce corrections in NGL and Gamma-Ray Logging results were explored, and a corresponding algorithm was substantiated and implemented.

- The employed methodologies allow for confident and reliable determination of the porosity and clay content of reservoirs with a high degree of accuracy.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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