Russian integrated approach to gas-bearing shaly sandstones log interpretation

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Abstract

In the region of Western Siberia among Russian major gas fields (Urengojskoye, Shtokmanskoe etc.) there present objects that combine high reservoir shaliness with low salinity of formation water. Presence of these two factors causes fundamental obstacles in reservoir detection, determination of saturation and estimation of HC reserves basing on log data.

We propose an integrated approach to petrophysical interpretation, which implies independent detection of clay and dense beds and solving of combined equations that represent petrophysical interrelations afterwards.

Described approach has been successfully implemented at many fields in Western Siberia. Applicability of equations described above is proved with vast volume of core material (tens of thousands of core samples with measured basic physical properties). Usage of data from wells drilled on oil base mud allows for better estimation of irreducible water content.

Introduction

Since their origin in 1930-s geophysical explorations in the former USSR have been developing mostly independently from their Western analogs and in turn they have been mostly closed for researchers from other countries. Some information interchange however existed and it contributed a lot to the development of geophysics and particularly petrophysics. Much of the developments of that period have been implemented in modern geophysical practice of Russia and former USSR countries. However for some reasons most of them remain unknown for Western community.

When the works of Russian authors started occurring in Western press a number of distinctions in kind was revealed between geophysical methods and data interpretation approaches that were used by Russian and Western schools. This issue became most topical when international geophysical companies started their business in Russia, as they were provided mostly with data obtained and processed by using technologies developed in USSR.

In this work authors will point out some distinctions between modern Russian and Western approaches to interpretation of well logs and petrophysical data.
and software for interpretation in Russia and worldwide will also be covered in this article. It’s worth noticing that most of the subjects in this article are not fully taken up in Western press and some of them are totally skipped.

I. Modern state of Russian geophysics

Foreign researchers may get acquainted with general representation of issues solved by modern Russian geophysics from book ‘Russian Style Formation Evaluation’ [8] however it mostly represents subjective opinion of its authors and can hardly be used for detail analysis of this issue.

Exploration geophysics has been under close consideration of State government in USSR and in Russia. In USSR there existed 4 dedicated journals, together with nonserials and digests that were devoted to acquisition and interpretation of geophysical data. Apart from that about 40 books were being published annually. However the total volume of publications has been severely reduced when USSR collapsed and has started restoring only in 2002.

3 to 5 workshops dedicated to exploration geophysics are held annually in Russia with their results being published in science press. Guidelines and instructions based on best practices of lead geophysicists are published periodically. About 10 institutes are qualifying graduates specializing at exploration geophysics, well logging and petrophysics.

Russia has been producing wide range of logging tools and core analysis equipment which covers most of its needs. International service companies introduced their equipment in the beginning of 1990-s, however their contribution to total amount of services in Russia remains insignificant.

II. Development of Russian petrophysics and interpretation of well logs

We’ll point out the priorities that have been guiding development of well logging data interpretation through all its history in USSR and have contributed to establishing of petrophysics as self-consistent area of applied science.

Estimation of porosity, permeability and clay content of terrigenous shaly gas-bearing formations has been remaining a topical issue in Russia since 1950-s to the present. In 1940-s and in the beginning of 1950-s the most interesting Western works related to petrophysics together with books of J.S. Pearson [40] and J.Amix - D.Bass - R.Whiting, covering physical aspects of oil-bearing formations, were translated into Russian and published in Soviet science

\[1^\text{In Russia subsoil areas are the State property. Special State Committees in charge possess control over reservoir exploration and development. Thus companies that operate in Russia must prove reasonableness of obtained results not only to Customer but also to Russian Government.}\]
press. This produced great impact on the development of data interpretation in shaly gas-bearing formations. Outstanding contribution to this matter was made by Soviet geophysicist V.N. Dakhnov together with his alumni and colleagues.

As rocks with high clay content represent most part of reservoir rocks in former USSR, petrophysics of these formations has been traditionally discussed separately. V.N. Dakhnov’s publications \cite{27, 28} were among the first contributions to the issue, they described influence of clay volume and distribution on resistivity of gas-bearing reservoirs. We’ll discuss further development of this matter in Section IX.

In 1960-s Soviet petrophysicist Sh.A. Guberman proposed using pattern recognition for separating the well logs into ‘water’ and ‘hydrocarbons’ categories. Recently this interpretational approach became very important, mostly in exploration geophysics \cite{42}.

Another approach is a regression analysis developed by M.M. Ellansky \cite{42}, which is based on statistical methods and can be applied at exploration stage as well as to the estimation of reserves.

Due to wide popularity of pattern recognition and regression analysis a number of methods have been developed that allow estimating relative efficiency of both these approaches. We’ll discuss these methods in detail in Section III.1.

A new era in quantitative interpretation begins in 1970-s, being stipulated by introducing of computers. Before personal computers were introduced, there had been developed several systems in USSR intended for interpretation of well logs: ‘Karotazh’, ‘ASOIGIS’ etc. These systems were introduced and further developed in more than 300 enterprises within USSR and Eastern Block countries (East Germany, Poland, Hungary, Bulgaria and Czechoslovakia). We’ll discuss further development of similar systems in Section VIII.

It’s worth noticing that Soviet researchers have developed methods of well logs interpretation being mostly isolated from international studies however Russian technologies in terms of efficiency are highly competitive with their Western analogs but are much cheaper.

III. Objective estimation of efficiency of data interpretation

Scientific environment of the USSR allowed of unrestricted development of alternative methods of data interpretation, such as pattern recognition or integrated radiometry. Apart from expert judgments and comparison of methods based on reasonableness of built-in assumptions, practical efficiency used to be a most
criterion of performance. Besides, a formalized empiric scheme was developed in Gubkin’s State University of Oil and Gas, which allowed estimating reasonableness of particular method’s application.

III.1. Method of division into categories ‘hydrocarbons’ – ‘water’

A method that allowed dividing well logs into categories ‘water’-‘hydrocarbons’ was proposed by Latysheva, Kuznetsov and Dyakonova. This method estimates uncertainty of such a division and should be applied to a robust dataset containing results of well tests. This method allows dividing well logs into categories ‘hydrocarbons’ – ‘water’ either directly, using apparent resistivity data of laterolog / lateral array / induction, or using processed data (true resistivity or water saturation) – depending on which parameter allows providing best division relative to its ‘critical’ value.

The simplest division may be performed by obtaining critical value of resistivity from the logs (assuming ‘water’ if resistivity value is below critical and vice versa). However if formations are highly heterogeneous, division based on critical resistivity is not efficient.

In this case true formation resistivity is used for estimation of water saturation.

Then correlation between formation resistivity and critical water saturation (for current reservoir type) is established.

This approach admits comparing efficiency of different methods intended for dividing into ‘water’-‘hydrocarbons’ categories, allowing a researcher to select the one best suitable for current geological environment and technology. Availability of testing area with parameters similar to natural environment, together with reliable estimates of its formations’ productivity is a mandatory usability condition of this approach. This method has been successfully implemented in USSR since 1960-s but hasn’t been adopted in Western practice.

III.2. Method of grouping

If estimation of reserves needs to be conducted at highly heterogeneous formations and core data is abundant while log data is spurious (for example due to high variations in mineral composition) a method of grouping may be used, which proposes dividing formations into homogeneous groups and estimating properties of each group separately.

L.B. Berman and colleagues has applied this method to shaly gas-bearing formations of many fields in the former USSR. Description of this method may be found at Russian log interpretation handbook.

The method is based on the assumption that for the purpose of reserves’ estimation it’s enough to select 3 to 7 groups
of objects within the studied reservoir. Let’s assume that there exist similar groups $A$ and $B$ and object $a$ belongs to $A$. Difference between porosity / permeability values of $a$ and porosity / permeability averages for $A$ must be much less than a difference between porosity / permeability averages for $A$ and $B$, which represents a division criterion.

Results of well tests and 3-stage testing, apart from the well logs, are used to conduct such a division. A number of modifications of this method have been developed that propose using various division approaches and criterions. Clustering has become the most popular recently, it either regards a composition of multidimensional distributions or realizes ISODATA algorithm.

IV. Concepts and petrophysical variables used in Russia

Here we point out some significant distinctions between Russian and Western petrophysics. The first distinction revealed in 1950-s when Soviet researchers refused using ‘worldwide average’ values of coefficients entering into petrophysical equations – such as for example saturation exponent N entering into Dakhnov-Archie equation of resistivity. Adjustment of these ratios by using core data was proposed instead.

Along with this innovation usage of complex (integral) parameters was introduced. First of them was proposed by I.M. Eidman and B.Yu. Wendelstein [24] and described surface conductance. It was defined as a ratio of formation resistivity factor obtained with saline mud to the formation resistivity factor obtained with fresh mud.

Relative shaliness $\eta_{cl}$ was also proposed by B.Yu. Wendelstein [24], it was defined as a ratio of clay volume fraction to the sum of porosity and clay volume fraction. In order to advance this parameter a relative cementation $\eta_{cem}$ parameter was later proposed by one of the authors in joint with B.Yu. Wendelstein. It was defined as a ratio of cement volume fraction to the sum of porosity and cement volume fraction.

These parameters have proved their efficiency at many fields by being applied to separating between reservoirs and non-reservoirs, estimating of surface conductance parameter, solving for bounded water content and rocks permeability. Section IX illustrates practical examples of their application.

$S_{w*}$ and $S_{w**}$ are also in use in Russian petrophysics, these are water saturation values measured correspondingly when oil content reaches 99% and when water content reaches 99%. They are rarely being referred to in Western publications.

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2 Logging, then well testing, then logging again – this approach allows to estimate variations in bottomhole area properties. This technology has been developed in USSR and hasn’t been adopted by Western practice.
V. Porosity, consolidation curves and cementation

Existence of gas in under-consolidated formations impels paying high attention to examining of how their properties (porosity, cement type and cement content) vary with depth. If reservoir rocks are constricted within 100-200 meters interval and abnormal high pressure is absent then porosity variations usually have a linear trend. However it is not true if near-surface formations are also in study (at depths less than 1200-1500 m).

Role of mechanical and chemical consolidation increases with depth and areas exposed to minerals’ (particularly carbonates) dissolution and deposition occur here and there, depending on water salinity and temperature gradient. Consolidation, abnormal high formation pressure, preservative effect of hydrocarbons on authigenous minerals’ generation, influence of mineral content of the rocks on alteration of their properties with depth - all these issues have been studied very closely in USSR and Russia [2, 39, 44].

There are many ways to state the equation of consolidation (performing generalization of Athy’s equation in various ways). In Russia it has become popular an equation of maximum porosity as a function of depth, similar to equation (1):

\[ \Phi = \frac{\Phi_0 \exp(-\alpha Z)}{1 + \beta \exp(-\alpha Z)} \]  

(1)

Here \( \Phi \) – porosity, \( Z \) – absolute depth. It’s assumed here that \( \Phi_0 \) is a relative 'initial porosity' (porosity at \( Z = 0 \)). Maximum porosity at this depth usually varies from 40% to 70%, depending on lithology. Ratio \( \alpha \) defines rate of maximum porosity decline, ratio \( \beta \) defines slowdown of this decline – these are empiric constants varying from 0 to 1.

It’s not very convenient to use equation (1) if \( \alpha, \beta \) and \( \Phi_0 \) are adjusted in interactive manner which is however necessary in order to account for regional features. To account for this, if depth range is limited, authors propose using equation (2):

\[ \Phi = \left[ \Phi_0^\alpha \left( \frac{Z-Z_0}{Z_i-Z_0} \right)^\beta + \Phi_1^\beta \left( \frac{Z-Z_0}{Z_i-Z_0} \right)^{\beta} \right]^{\frac{1}{\beta}} \]  

(2)

Here \( \Phi_i \) – porosity, \( Z_i \) – absolute depth. This equation is more convenient for interactive adjustment: if \( Z=Z_0 \) then \( \Phi(Z_0) = \Phi_0 \), if \( Z=Z_i \) then \( \Phi(Z_i) = \Phi_1 \), while maximum porosity decline rate and slowness are controlled by adjusting of empiric \( \alpha \) and \( \beta \) coefficients that may vary from 0 to 1.

VI. Some features of petrophysical interrelations that are being used in Russian geophysical applications
A set of physical methods used by Russian geophysicists to study shaly gas-bearing reservoirs is generally similar to the one used by Western researchers. Resistivity, self-polarization, natural radioactivity, sonic, neutron and density methods are in use. Since the middle of 1990-s CMR, C-O and CHFR logging have been performed on a regular basis.

Petrophysical equations used for data interpretation (except relations for resistivity, SP, permeability and transit time) are generally similar to the ones used in Western practice [1-6, 14, 16-24].

Equations similar to Simandoux and Puppon-Levoux (Indonesia) are widely used in well-known Western petrophysical software (ELAN, Geolog etc) however they are generally not used in Russia.

Core investigations are traditionally paid much more attention in Russia then in other countries. If discovered field possesses significant reserves then amount of investigated core samples may reach several thousands. Results of core investigation are widely used for normalization of petrophysical equations. This tendency to usage of empirical information has caused occurrence and wide application of Larionov-Schwarzman's equation of natural radioactivity. This equation had been initially proposed for carbonates only and was afterwards widely popularized by W.H. Fertl.

Below we are describing some equations widely used in Russia for interpretation of logging data.

M.M. Ellansky jointly with one of the authors have proposed resistivity equations that account for clay content and have become in USSR most well-known equations of this type. As it's shown in the book [44], most of known resistivity equations become equal by first order when being expanded into Taylor series. It's therefore reasonable to select those ones that remain mathematically correct at their limiting values (for example if porosity or clay content is equal to zero).

These equations assume that conductivity of the rock exists due to dissolution of its components in mud and their distribution in clays [3-7, 14, 18, 20-24, 34, 43, 44]. The simplest equation of this type is a generalized form of Lihtenekker-Roter equation (3):

$$\frac{R_t}{R_w} = \Phi^m R_{mix}$$  \hspace{1cm} (3)

Here $R_t$ – true formation resistivity, $R_w$ – resistivity of formation water, $R_{mix}$ – resistivity of clay and water mix, $m$ – empirical constant which depends on cementation.

$$\frac{R_{mix}}{R_w} = \left(1 + \frac{\Phi_{cl} V_{cl}}{\Phi S_w} \left(\frac{R_{cl}}{R_w}\right)^\alpha - 1\right)\frac{1}{\alpha}$$  \hspace{1cm} (3a)
Here \( R_{\text{mix}} \) – resistivity of clay and water mix, \( R_w \) – resistivity of formation water, \( \Phi \) – porosity of rock, \( \Phi_{cl} \) – clay porosity, \( V_{cl} \) – clay content, \( \alpha \) - adjustable structure constant which may vary from 0 to 1. This equation may obviously be regarded as Dakhnov-Archie’s equation multiplied by a correction which replaces \( R_w \) with \( R_{\text{mix}} \).

Setting \( \alpha = -1 \) will produce equation proposed by M.M. Ellansky, which successfully describes lots of empirical data (particularly data taken from Waxman-Smith’s publication well-known to Western community). These equations are widely known in Russia and are being applied to a wide range of objects.

Equation for \( \alpha_{sp} \) may be derived similarly. It has a simple form (4), where \( R_{\text{mix}} \) is derived from equation (3a):

\[
\alpha_{sp} = \frac{R_{\text{mix}} - R_{cl}}{R_w - R_{cl}} \tag{4}
\]

Here \( R_{\text{mix}} \) – resistivity of clay and water mix, \( R_w \) – resistivity of formation water, \( R_{cl} \) – resistivity of clay, \( \alpha_{sp} \) varies from 0 to 1.

Equation proposed by M.M. Ellansky (5) possesses similar grade of approximation [44]:

\[
\alpha_{sp} = \left(1 - \frac{\Phi_{cl}(V_{cl} - V_{cl,\text{MIN}})}{\Phi S_{so}}\right)^C \tag{5}
\]

Here \( \Phi_{cl} \) – clay porosity, \( V_{cl} \) – clay content, \( V_{cl,\text{MIN}} \) – minimum clay content, \( S_{so} \) – saturation of invaded zone, \( C \) is an adjustable structure constant which may vary from 0 to 1.

Transit time equation may be regarded separately. Empirical equation (6) has been proposed by V.T. Fomenko and is currently being widely applied to log data interpretation of shaly sands of Western Siberia. Special corrections are to be applied in case of gas-bearing reservoirs:

\[
\Delta T = A + \frac{B\Phi^2}{\sqrt{\alpha_{sp} - 0.05}} \tag{6}
\]

Here \( \Phi \) – porosity, \( \alpha_{sp} \) may be derived from (5), constants A and B may vary within wide ranges (A: 166-180, B: 0.175-0.258).

Additional interrelations that relate parameters \( \Phi \) (porosity) and \( S_{\text{wirr}} \) (bound water content) to physical properties of the rock are usually presented in views (7)-(8):

\[
\Phi = \Phi_{\text{matrix}} - V_{cl} - V_{\text{carb}} \tag{7}
\]

Here \( \Phi \) – porosity of the rock, \( \Phi_{\text{matrix}} \) – porosity of the rock’s matrix, \( V_{cl} \) – clay content, \( V_{\text{carb}} \) – carbonates content.

\[
S_{\text{wirr}} = S_{\text{wirr,MIN}} + \frac{\Phi_{\text{no, res}} + \Phi_{cl} V_{cl}}{\Phi} \tag{8}
\]

Here \( S_{\text{wirr}} \) – bound water content, \( S_{\text{wirr,MIN}} \) – minimum bound water content, \( \Phi \) – porosity of the rock, \( \Phi_{cl} \) – clay porosity, \( \Phi_{\text{no, res}} \) – porosity of non-reservoir rock, \( V_{cl} \) – clay content.
Equation (1) may be used for estimating of $\Phi_{\text{matrix}}$ in (7), while variables $S_{\text{wirr,MIN}}$ and $\Phi_{\text{no_coll}}$ are adjusted by taking into account formation lithology (including clay type and clay cement content).

The following equation has become popular in Russia for estimating $S_{\text{wirr}}$:

$$S_{\text{wirr}} = S_{\text{wirr,MIN}} + A\eta_{\text{cen}} = S_{\text{wirr,MIN}} + \frac{A(V_{cl} + V_{\text{carb}})}{V_{cl} + V_{\text{carb}} + \Phi}$$ (9)

Here $S_{\text{wirr}}$ – bound water content, $S_{\text{wirr,MIN}}$ – minimum bound water content, $V_{cl}$ – clay content, $V_{\text{carb}}$ – carbonates content, $\Phi$ – porosity of the rock, $A$ is a constant which is derived from statistical analysis of core investigations.

In the end of this section we present some equations used for calculation of permeability in shaly sands. Apart from simplest equations like (10), equations similar to (11) are applied in Russia widely:

$$\log K = \log K_{\max} + \left(\log K_{\max} - \log K_{\min}\right)\left(\Phi - \Phi_{\min}\right)$$

$$\log K = A + B \log \left(\Phi \left(1 - S_{\text{wirr}}\right) - C\right) + D \log S_{\text{wirr}}$$ (11)

Here $\Phi$ – porosity of the rock, $\Phi_{\min}$, $\Phi_{\max}$ - extremum porosity values, $K$ – permeability of the rock, $K_{\min}$, $K_{\max}$ – extremum values of permeability, $S_{\text{wirr}}$ – bound water content, $A$, $B$, $C$ and $D$ – empiric adjustable constants.

VII. Adjustment of petrophysical interrelations by using core data and logs

Parameter correlations and model validation in petrophysics have been traditionally obtained by using graphical data analysis. This was the only possible method in precomputer era, while attempts of explaining multidimensional relationships through two-dimensional charts usually required much of inventiveness. Modeling in petrophysics thus added up either to selecting variables or their conversions that allowed visualizing some interrelations or to dividing heterogeneous data into the classes distinctive in kind.

Petrophysical interrelations vary against different rock types, especially if structural properties (resistivity, permeability etc) are concerned. If sedimentation of various types of facies or postsedimentation transformation is concerned, this change can’t be accounted for by rocks’ classification based solely on stratigraphy. These cases require joint analysis of formation features (usually revealed by cross-plots of core data) and sedimentology [7, 10, 15, 17, 38].

It’s proved in sedimentology that granulometry parameters of formations generated in various conditions (particularly in sedimentary environments with different energy) are different, especially concerning first moments of grain-size distribution curves. Example of this case is shown at Fig. 1a and 1b. This correlation diagram, also known as cross-plot of L.B. Rukhin,
differentiates between various sedimentary environments. A region with maximum permeability (marked with pink color) is clearly distinguished here.

Various cross-plots intended for adjustment of petrophysical interrelations and rocks classification are widely discussed in literature together with statistical methods. Cross-plots of 3 variables (X-Y-Z) have become most popular in Russian petrophysics and log interpretation, we are presenting most widely used of them in Table 1:

Data clustering and adjustment of coefficients together with log data processing may exist in order to supplement data visualization. However, petrophysical inversion is a separate issue.

**VIII. Usage of optimization inversion in quantitative interpretation and its features in Russia**

Methods of data interpretation that are applied in Russia to describing of shaly gas-bearing reservoirs (and software that realizes them) can be conditionally divided into 2 groups:

- Simplified (express) methods;
- Methods based on optimization inversion [13, 26, 30-33, 37, 41].

Simplified methods use approximation of some variables in equations (for example, gas influence in neutron moisture or density equations). Methods based on optimization inversion use a set of interrelationships that aggregate up-to-date conceptions of nature character.

Inversion may be conditionally added up to minimization of difference between measured and modeled log data. The more complement the system of equations is (if coefficients set up correctly) - the more reliable results of data interpretation are obtained.

In 1967 Soviet researcher L.A. Halfin [41] proposed a theory that allowed using inversion for interpretation of geophysical data. Generally petrophysical interrelations may be regarded as 2 basic types of stochastic interrelationships that allow estimating vector X (source properties) out of vector Y (log data with errors), if equation (12) is known:

\[
y_j = f(x_1, x_2, ..., x_n, A_i, S_j) + \left(0 + P_j E_{y_j S_j} + P_j E_{y_j S_j}^2\right) \tag{12}
\]

Coupling equations (13) describing interrelations between decision variables (source parameters) may be used supplementary:

\[
g_j(x_1, x_2, ..., x_n, A_i, S_j) = \left(0 + P_j E_{y_j S_j} + P_j E_{y_j S_j}^2\right) \tag{13}
\]

Here \(x_i\) – desired properties, \(y_j\) – log data, \(A\) – empiric constants, \(P\) – probability of gross errors, \(S\) – random error variance, \(E_{y_j S_j}\) - random errors that possess zero expectation and root-mean-square error \(S_j\)
Both desirableness of selection from a number of alternative interrelationships and robustness (low probability of crude errors) have been taken into account in these equations.

Software intended for inversion of log data have been first developed in USSR by one of the authors. It was 'PETROFISIKA' compound of 'C-2' complex (Enikeev, 1974). In Western geophysics similar software named GLOBAL was developed by Subbit and Mayer in 1980 [13]. Hashmi has developed similar ULTRA software in 1985.

Data inversion has become very popular and has been implemented into most well-known systems intended for log data processing and interpretation. Methods of inversion can be divided into optimization, statistical and model.

Software products PRIME-OPTCOM, GINTEL-2000, GEOOFFICE SOLVER, and ModERn have been developed and are currently mostly used in Russia. ELAN+, GEOLOG and POWERLOG are also well-known in Russia although are not in common use. Convergence and robustness of optimization algorithm are usually not published in press. It’s known, however, that efficiency of software packages developed in Russia is checked with a complex system of tests.

**IX. Practical examples of core data generalization**

Here we present some examples of core data processing that explain usage of the petrophysical statements mentioned above.

Core data has been derived from the samples of shaly gas-bearing reservoirs of gas field which is located in Western Siberia. As it’s seen from Fig. 2a and 2b, the values of clay and siltstone content in current formations are on average higher than that of other fields that are located within the same region (all diagrams in this article were drew by using **ModERn™** software).

This difference in rocks’ constitution predetermines discrepancy between reservoir properties, which is shown at Fig. 3a, 3b:

Relative content of clay and carbonate cement has great influence on bound water content, which in turn predetermines permeability and relative permeability of the formations. This is illustrated at Fig. 4a, 4b, 5a, 5b:

**X. Examples of quantitative interpretation results**

Here we present example of log data interpretation made by using **ModERn™** software. It possesses an option of interactive adjustment of coefficients entering into the equations similar to (12) and (13). It’s worth mentioning that this
feature is not common for most of known petrophysical software. Fig. 6 illustrates application of this option to the insufficient set of core data.

Conclusion

During long period of time petrophysics in Russia had been developing mostly separately from other world and investigated areas poorly studied by Western schools. Original approaches in theory and practice have been developed, particularly for interpretation of shaly gas-bearing reservoirs.

Generally Soviet petrophysics was developing in 2 main directions:

1. Specification of petrophysical equations;

2. Complexation of geological and geophysical information and its joint interpretation by using methods of data inversion.

REFERENCES


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FIGURES

Fig. 1a. Correlation diagram of grain sorting versus median grain diameter graded by logarithm of porosity. Graduations within specified ranges are indicated with designated colors (pink color corresponds to maximum porosity).

Fig. 1b. Correlation diagram of grain sorting versus median grain diameter graded by logarithm of permeability. Graduations within specified ranges are indicated with designated colors (pink color corresponds to maximum permeability).
Fig. 2a. Correlation diagram of clay content versus siltstone content graded by field code. Samples of current field are indicated with blue dots, pink dots indicate samples of other nearby fields.

Fig. 2b. Correlation diagram of clay content versus siltstone content graded by sand content for current field.

Fig. 3a. Correlation diagram of clay content versus porosity graded by absolute depth.

Fig. 3b. Correlation diagram of carbonate and clay content versus porosity graded by absolute depth.

Fig. 4a. Correlation diagram of porosity versus bound water content graded by logarithm of permeability.
Fig. 4b. Correlation diagram of relative clay cement content (ETA) versus bound water content, graded by permeability.

Fig. 5a. Correlation diagram of porosity versus permeability graded by field code, samples of current field are indicated with blue dots, other colors indicate samples taken from nearby fields.

Fig. 5b. Correlation diagram of porosity versus permeability graded by relative clay cement content (ETA).

Fig. 6a. Interactive adjustment of coefficients entering into equation (12) by using values in gas-bearing shaly sands as a reference (screenshots of ModERn™ software).
Fig. 6b. Interactive adjustment of coefficients entering into coupling equation (13) by taking into account a priori information (screenshots of ModERn™ software).
TABLES

Table 1. Petrophysical cross-plots widely used in Russia

<table>
<thead>
<tr>
<th>№</th>
<th>Name</th>
<th>Variables</th>
<th>Applied to</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Slichter-Kozeni</td>
<td>$\Phi - K - ?^3$</td>
<td>Correlation between porosity and permeability</td>
<td></td>
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<tr>
<td>2</td>
<td>Athy (1930)</td>
<td>$\Phi - Z - ?$</td>
<td>Consolidation of rocks</td>
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<tr>
<td>3</td>
<td>Dakhnov</td>
<td>$\Phi - F - ?$</td>
<td>Estimation of porosity</td>
<td></td>
</tr>
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<td>4</td>
<td>Archie (1941)</td>
<td>$S_w - Q - ?$</td>
<td>Estimation of saturation influence</td>
<td></td>
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<td>5</td>
<td>Leverett</td>
<td>$S_w - K(S_n) - R$</td>
<td>Normalization of relative permeability curves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kobranova (1960)</td>
<td>$V_d - \Phi - ?$</td>
<td>Division between reservoir and non-reservoir rocks</td>
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$^3$ Any other parameter
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<th></th>
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<th>Equation/Formula</th>
<th>Description</th>
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<td>6</td>
<td>Wyllie-Nechai-Zalyaev</td>
<td>$N_k - R_t - S_w$</td>
<td>Normalization for estimation of saturation</td>
</tr>
<tr>
<td>7</td>
<td>Hingle-Pickett</td>
<td>$\Phi - R_i - S_w$</td>
<td>Correlation between porosity and resistivity (Pickett proposed using dual log scale)</td>
</tr>
<tr>
<td>8</td>
<td>Wyllie-Pirson</td>
<td>$\Phi - S_w - K$</td>
<td>Correlation between 3 reservoir properties</td>
</tr>
<tr>
<td>9</td>
<td>M.R. Wyllie</td>
<td>$\Phi - dT - \omega$</td>
<td>Normalization used for estimation of lithotype</td>
</tr>
<tr>
<td>10</td>
<td>Fatt I.</td>
<td>$P - K - \omega$</td>
<td>Influence of pressure on permeability</td>
</tr>
<tr>
<td>11</td>
<td>Toomeer</td>
<td>$\text{Sw}_i - P_i - R$</td>
<td>Normalization of displacement curves</td>
</tr>
<tr>
<td>12</td>
<td>Krumbein-Folk-Rukhin</td>
<td>$\text{Md} - \text{So} - J_1$</td>
<td>Correlation between grain size &amp; lithology</td>
</tr>
<tr>
<td>13</td>
<td>Wendelstein B.Yu.</td>
<td>$V_{cl} - \Phi - \text{ETA}_{cl}$</td>
<td>Reservoir differentiation</td>
</tr>
<tr>
<td>14</td>
<td>Ellansky M.M.</td>
<td>$\Phi - P - (V_{cl}/\Phi)$</td>
<td>Differentiation based on clay content in pore volume ratio</td>
</tr>
<tr>
<td>15</td>
<td>Pangea-1</td>
<td>$V_{cl} - V_{silt} - Z$</td>
<td>Correlation of clay content and siltstone content within lithotypes</td>
</tr>
<tr>
<td>16</td>
<td>Pangea-2*</td>
<td>$\Phi - (V_{cl} + V_{carb}) - Z$</td>
<td>Prediction of maximum porosity versus depth</td>
</tr>
<tr>
<td>17</td>
<td>Pangea-3*</td>
<td>$\Phi - Z - \text{lg(K)}$</td>
<td>Prediction of reservoirs' existence</td>
</tr>
</tbody>
</table>

* These cross-plots have no systematic usage in literature; however they are often used by the authors.