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DETERMINATION OF HYDROCARBON SATURATION, ROCK COMPOSITION, POROSITY AND PERMEABILITY IN CLAYEY–SILTY SANDSTONES EXHIBITING SANDWICH-TYPE DEVELOPMENT

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A new interpretation system for hydrocarbon-bearing sandstones (COMWELL–B. R./ELGI) has been developed based on an earlier theory. This theory has further been developed so that sandstones are treated as composed of 8 components, viz. 1) impermeable shale laminae in the sandwich-type sandstone, 2) swelling-type clays, 3) nonswelling clays, 4) silt, 5) sand, 6) carbonate, 7) porosity in the permeable thin laminae, 8) adsorption water porosity. The interpretation system is built up on a statistical basis in the framework of an overdetermined mathematical treatment of the unknown quantities. However, the system is of modular nature enabling it to be divided into deterministic subsystems. A sequential calibration possibility is provided by the subsystems.

The new technique for evaluating the hydrocarbon saturation involved in this system is of special interest since routine techniques frequently fail in sandwiches. Besides the theoretical and practical aspects, a field example is shown from an oil- and gas-reservoir.

Keywords: shaly sandstone model, anisotropic model, dispersed clay and silt, laminated clay and silt, lithologic influence factor

1. Introduction: Problem performance

Oil/gas-bearing sandstones in Hungary are of fine-grained clayey–silty (sometimes calcareous) development and frequently follow a laminated "sandwich-type" depositional pattern. Well-log interpretation difficulties associated with this kind of lithology are further increased by fresh water in the reservoirs. Under these conditions hydrocarbons may not be recognized by current routine interpretation techniques since the electric resistivity of the said formations is near to the resistivity of water-bearing clean sand.

Sharp resistivity reductions in pay zones are caused by three main effects [Barlai 1969, 1972, 1974]:

1. Resistivity of the interlaminated shale streaks is only 1.3–2.0 Ωm whereas that of the water-bearing sand is 4–10 Ωm, consequently the longitudinal resistivity, R_L, of the laminated anisotropic formations will not be significantly higher than the resistivity of the shale if relative volume, p, of the latter is large ($p > 0.2$);

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2. Within the permeable sand laminae the electric conductance of the cationic adsorption water, covering the clay and silt grains, is high resulting in an additional resistivity reduction of the permeable interbeddings;
3. Irreducible water saturation is high ($S_{wi}=0.4$–0.6) in the clayey–silty sands because of the small pore sizes and the associated large specific surface area of the pores. The resistivity will be further reduced by the high irreducible water saturation.

Permeability performance of the said formations is also complex and shows great variations and often goes below the permeability cutoff, especially in calcareous sandstones since a part of narrow pore channels will be blocked by the carbonate.

A great deal of effort has led to some results being achieved in Hungary [Barlai 1969, 1972, 1974, 1976, 1981] in helping to solve well-log interpretation difficulties. The technique used has been incorporated in a computerized well-log interpretation system called COMWELL–B. R./ELGI. The following main constituents are involved in this system:

1. An anisotropic sandstone model of nine components;
2. Multicomponent response functions of the main well-logging parameters;
3. A comprehensive program package put on a hybrid basis of a great number of deterministic and statistical procedures of interpretation;
4. A special calibration system covering the total interpretation flow;
5. A special technique for evaluating water saturation in sandwiches (based on the concept of multiple comparison);
6. A variety of interpretation outputs covering volumetric rock components, porosity- and fluid saturation terms, hydraulic- and capillary properties, and a detailed delineation of the reservoir related to the probable recovery and production behaviour of the individual zones.

2. Anisotropic sandstone model of nine components

To cope with the said problems an anisotropic sandstone model of nine components has been developed. The model is composed of a fourfold shale, a threefold porosity system, and a double-component inert matrix, as shown in *Fig. 1*. The shale has been distributed into:

- impermeable shale laminae with a volumetric fraction p; thus the permeable interbeddings have a volumetric fraction $(1-p)$;
- disseminated clay, V_{cl}, within the permeable laminae; this component has further been divided into swelling and nonswelling clays: $V_{cl,\ sw}$ and $V_{cl,\ nsw}$, respectively:
- silt, V_{si}, also within the permeable interbeddings.

All these shale components are characterized by their own geophysical properties and they differ very much from each other. Consequently, any kind of merging/averaging might lead to serious misunderstanding of the logging parameters and misleading errors in their interpretation especially when saturation

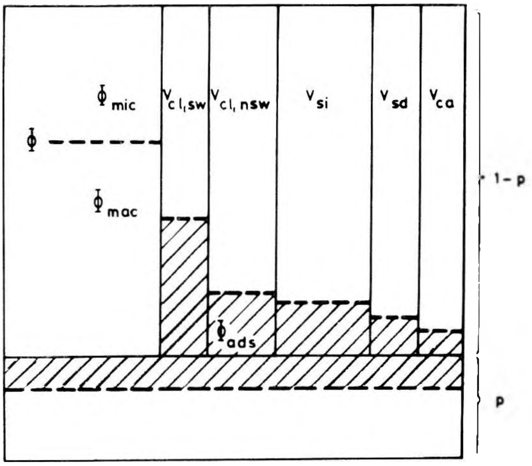


Fig. 1. Volumetric model of shaly sandstone. p — relative volume of impermeable shale laminae. Components of shale within the permeable laminae: $V_{cl,sw}$ — disseminated swelling clay, $V_{cl,nsw}$ — disseminated nonswelling clay, V_{si} — silt. Components of the matrix: V_{sd} — sand, V_{ca} — carbonate. The pore system in the permeable laminae: Φ — effective porosity (Φ_{mac} — effective macro porosity, Φ_{mic} — effective micro porosity), Φ_{ads} — porosity of adsorption water

1. ábra. Agyagos homokkő térfogati modellje. p — impermeábilis agyagmárga csíkok relatív térfogata. A permeábilis kőzetcsíkokon belüli agyag komponensek: $V_{cl,sw}$ — duzzadó agyag, $V_{cl,nsw}$ — nem duzzadó agyag, V_{si} — kőzetliszt. A mátrix komponensei: V_{sd} — homok, V_{ca} — karbonát. A pórusrendszer a permeábilis kőzetcsíkokban: Φ — effektív porozitás (Φ_{mac} — effektív makroporozitás, Φ_{mic} — effektív mikroporozitás), Φ_{ads} — adszorpciós porozitás

Рис. 1. Объемная модель глинистого песчаника. p — относительный объем прослоев непроницаемых глинистых мергелей. Глинистые компоненты в пределах проницаемых прослоев: $V_{cl,sw}$ — глины набухающие, $V_{cl,nsw}$ — глины ненабухающие, V_{si} — алевриты. Компоненты цемента: V_{sd} — пески, V_{ca} — карбонаты. Система пор в пределах проницаемых прослоев: Φ — эффективная пористость проницаемых прослоев (Φ_{mac} — эффективная макропористость проницаемых прослоев, Φ_{mic} — эффективная микропористость проницаемых прослоев), Φ_{ads} — адсорбционная пористость

is concerned. A similar tendency to distinguish the shale components can be seen with SARABAND [Poupon et al. 1970] and with CLASS [Fertl 1981].

The pore system has been divided into:
- effective porosity, Φ
- porosity of adsorption/hydration water, Φ_{ads}.

The effective porosity has further been distributed into:
- effective macro porosity, Φ_{mac},
- effective micro porosity, Φ_{mic}.

Φ_{mac} and Φ_{mic} are separated from each other by the size of the equivalent hydraulic radius of the pores: the bound between them is at $3 \cdot 10^{-4}$ cm. This kind of separation is of importance since high irreducible water saturations, low resistivities and low permeabilities will occur in high micro porosity even if the total porosity of the rock is relatively high. The total porosity is the sum of the effective porosity and the hydration water porosity:

$$\Phi_t = \Phi + \Phi_{ads} = \Phi_{mac} + \Phi_{mic} + \Phi_{ads} \tag{1}$$

Finally the inert part of the rock matrix has been divided into:
- sand, V_{sd},
- carbonate, V_{ca},

since, if this were not done, porosity and permeability interpretations would fail in the case of calcareous sandstones.

3. Response functions of well logging parameters

At present seven logging parameters are incorporated in COMWELL-B.R./ELGI, viz:
- SP reduction factor, α
- gamma-ray intensity, I_{GR};
- bulk density, ϱ_b;
- neutron limestone porosity, Φ_{Nlm};
- acoustic propagation time of compressional waves, Δt;
- true resistivity of uncontaminated zone, R_t;
- flushed zone resistivity, R_{xo}.

Obviously the introduction of further advanced logging inputs (spectral gamma, acoustic shear waves, etc.) into the interpretation system is possible.

Response functions of logging parameters have been introduced to the system on a multicomponent basis corresponding to the 9-component sandstone model. With regard to the elucidation of the response functions, references [Barlai 1972, 1974, 1981] should be consulted. However, it is mentioned that with regard to the resistivity, R_t, of the sandstones the central role of accounting for the shale effects has been put in COMWELL-B. R./ELGI on the "lithologic influence factor", L, which is a ratio of the electric surface conductance, C_p, of the pores to the volume conductance C_Φ, of the effective pore space (when the latter is water-filled):

$$L = \frac{C_p}{C_\Phi}. \tag{2}$$

L comprises the individual effects of the rock components in the permeable isotropic interbeddings:

$$L = \left(\frac{V_{cl,\ sw}}{R_{cl,\ sw}} + \frac{V_{cl,\ nsw}}{R_{cl,\ nsw}} + \frac{V_{si}}{R_{si}} + \frac{V_{sd}}{R_{sd}} + \frac{V_{ca}}{R_{ca}}\right)\frac{R_w}{\Phi} \tag{3}$$

By analysing the correspondence with the SHELL [see for example JUHÁSZ 1981] and the Schlumberger dual-water [see for example BEST et al. 1978] models, we concluded that the formal analogous quantities of the said models – at least in water-bearing rocks – are:

$$L \sim BR_W Q_V \tag{4}$$

for the SHELL model,

$$L \sim S_{WB} \frac{R_{WF} - R_{WB}}{R_{WB}} \tag{5}$$

for the dual-water model. The meaning of the symbols is explained in references [JUHÁSZ 1981] and [BEST et al. 1978]

4. Hybrid interpretation system in COMWELL–B. R./ELGI: deterministic and statistical ways: system-calibration

The most complete form of geophysical interpretation has been offered by the statistical way [HOLTZMAN 1975; SALÁT et al. 1982; MAYER et al. 1981], since all available logging parameters can simultaneously be introduced into it in a weighted form, where the relative weights of the individual logging inputs, W_i, are determined by their reciprocal standard errors, $1/\sigma$. The system is mathematically "overdetermined" since the number of inputs is greater than that of the outputs, with the intention of reducing the production of errors in the outputs.

COMWELL–B. R./ELGI has been put on statistical basis, similarly to GLOBAL [MAYER et al. 1981], however the former is of hybrid nature since the deterministic way of interpretation has also been preserved in three forms:

1. Preliminary stage of interpretation is performed in it by deterministic subsystems, where the mathematical solution is "unique", i.e. the number of inputs is equal to those of outputs. In this way the mathematical treatment is more simple and fast – these features being important in the preliminary stage;
2. Deterministic subsystems follow each other in sequential form and only a small number of outputs are determined within one step. The individual steps can be self-calibrated and error propagation can be restricted in this way;
3. Calibration of the deterministic subsystems is easily performed by means of cross-plots; the first set of system-constants will then be determined.

The final calibration of the system-constants is still performed by statistical optimization. In doing so quadratic deviations of theoretical values of the logging parameters from the measured ones will be minimized for the total evaluated borehole section.

Error analyis is an important part of all statistical systems, thus also of COMWELL–B. R./ELGI. Instead of analytical derivation, the method of finite differences (i.e. the ratio of finite differences) is applied since it is very fast and reliable. Random errors of corrections, response functions and interpretation outputs are estimated by the Gauss error propagation theorem. Systematic errors are diminished by statistical comparison of interpretation outputs with statistically representative core data.

A special system-logic is incorporated in COMWELL–B.R./ELGI, namely deterministic and statistical subsystems support each other in a hybrid form in order to arrive at the final convergence of the solutions with a good accuracy at a relatively low cost.

5. Determination of water saturation in sandwiches on the basis of comparison

The determination of the water saturation in sandwiches is an unsolved problem of log analysis [Barlai 1967; Vajnar et al. 1977; Bos 1982; Allen 1984] under the conditions when $R_p < R_0$. Here R_0 is the resistivity of the permeable laminae if they were water-filled; and R_p is the resistivity of the nonpermeable interbeddings. Since longitudinal resistivities of these formations are very low, movable hydrocarbon reserves in the permeable laminae often cannot be revealed at all.

COMWELL–B.R./ELGI introduced a special technique of comparison to evaluate the water saturation in sandwiches; a threefold comparison is applied:

1. Comparison of $(R_t)_s$ with $(R_{xo})_s$ where subscript s represents the permeable laminae;
2. Comparison of the theoretical log responses with the measured ones;
3. Comparing the logging properties at the investigated depth with the same properties of adequate reference layers, where the water saturation should be known with a fair accuracy from other information (e.g. the reference layer is water-bearing, thus $S_w = 1.0$).

In this way the effects of some systematic errors of the total logging and evaluating job will be reduced. Moreover R_w, R_{mf} and Φ will also be eliminated from the evaluation process. We are of the view that the evaluation of water saturation can appreciably be improved in this way, i.e. by combining the absolute and the comparative determinations.

6. Interpretation outputs determined by COMWELL–B.R./ELGI

Besides the evaluation of solid rock components (p; $V_{cl\,sw}$; $V_{cl\,nsw}$; V_{si}; V_{sd}; V_{ca}), porosity terms (Φ_{mac}, Φ_{mic}, Φ, Φ_{ads}, Φ_t) and saturation components (S_w, S_{wi}, S_{wm}; S_{hy}, S_{hyr}, S_{hym}) related to the effective porosity, the saturation terms are evaluated also–as related to the total porosity (S_{wt}, S_{hyt}, etc.).

As an example the formula for evaluating the adsorption/hydration water-filled porosity is shown here:

$$\Phi_{ads} = L\Phi \frac{R_{ads}}{R_w}, \tag{6}$$

where R_{ads} is the resistivity of the adsorption/hydration (i.e. "bound") water.

Permeability, k, is evaluated from a combination of the lithologic influence factor, L, and the effective porosity, Ω, through the hydraulic equation by Kozeny–Carman [KOZENY 1927; CARMAN 1956]. In addition, the specific surface area, S_p, of the rock can also be estimated [BARLAI 1976].

Residual hydrocarbons, S_{hyr}, are determined from Φ/k on the basis of calibration with core data; for this purpose S_{hyr} is obtained from relative permeability measurements. S_{wi} is obtained from a combination of the lithologic influence factor and the porosity [BARLAI 1974]. Some capillary properties can also be determined [Barlai et al. 1981], thus:

P_{displ} – capillary displacement pressure;
G – pore geometric factor;
$\bar{P}_c$ – a representative average capillary pressure of the pores, corresponding to the average hydraulic radius of the interconnected pores.

The capillary properties are related to each other by the following formula [BARLAI 1981]:

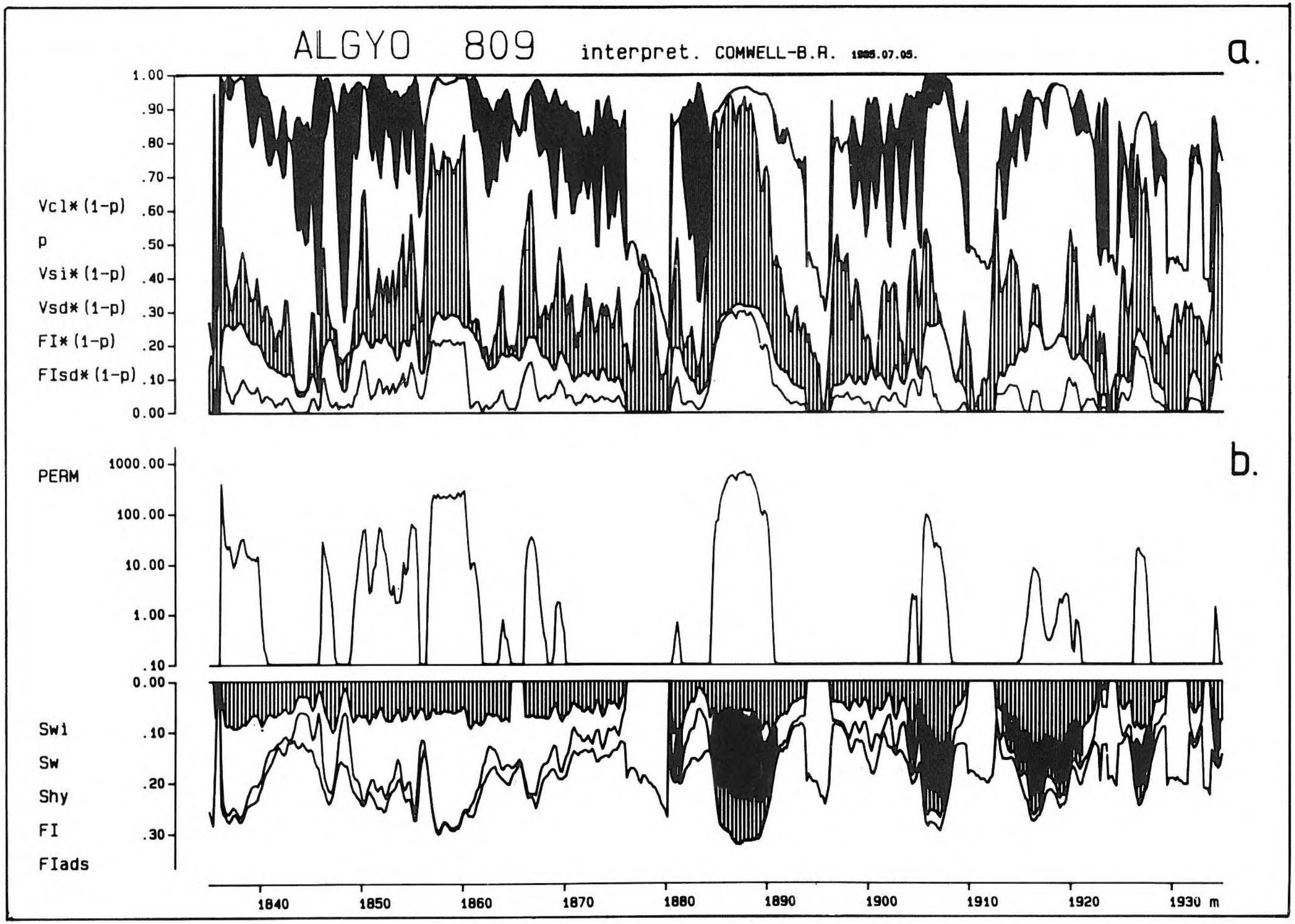
$$\bar{P}_c = P_{displ} \cdot e^G \tag{7}$$

Last but not least, a detailed delineation of the reservoir regarding the possible recovery behaviour of the individual zones can be achieved by utilizing the variety of interpretation outputs [BARLAI 1981]. This kind of delineation may contribute to production control of the reservoir especially when enhanced recovery technologies are concerned.

7. Field example utilizing COMWELL–B. R./ELGI

Outputs of application are presented in *Fig. 2* in borehole ALG-YO No. 809 of the Algyő field in Hungary. In *Fig. 2/a* the volumetric composition of the geological sequence, incorporating shaly sandstones and impermeable shales, is shown. In this case Φ, Φ_{mac}, Φ_{mic}, V_{sd}, V_{si}, p and V_{cl} as rock forming components have been taken into account in the interpretation model. It seems from the output plot that a great amount of V_{si}, p and V_{cl} are present in the shaly sand, and in a number of layers $\Phi_{mic} > \Phi_{mac}$ which is an indication of poor hydraulic properties.

In *Fig. 2/b* the permeability and fluid saturation plots are presented. The top section from 1835 m to 1878 m is water-bearing, the bottom section from 1880 m to 1937 m is oil-bearing. It seems that variations of permeability, k, correlate well with rock composition, the latter having been shown in Fig. 2/a.


ALGYO 809 interpret. COMWELL-B.R. 1985.07.05.
a.
Vcl*(1-p)
p
Vsi*(1-p)
Vsd*(1-p)
FI*(1-p)
FIsd*(1-p)
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0.00
b.
PERM
1000.00
100.00
10.00
1.00
.10
0.00
.10
.20
.30
Swi
Sw
Shy
FI
FIads
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930 m

In the lowermost section of the combined plot of fluid-saturations, the adsorption porosity Φ_{ads} is shown; then the residual oil $S_{hy,r}\,\Phi$ and the moved oil $S_{hy,m}\,\Phi$ are presented. The movable water $S_{w,m}\,\Phi$ is shown without any shading; the uppermost section presents the irreducible water $S_{w,i}\,\Phi$. It is to be noted that all the fluid components have been related to the effective porosity Φ, however, the sum of Φ and Φ_{ads} results in the total porosity Φ_t of the rocks in Fig. 2/b.

Fig. 2. Well-log analysis of borehole ALGYO–809 at Algyő
a) Volumetric rock composition vs. depth $V_{cl}*(1-p)$ — clay; p — impermeable shale laminae; $V_{si}*(1-p)$ — silt; $V_{sd}*(1-p)$ — sand; $FI*(1-p)$ — effective porosity; $FI_{sd}*(1-p)$ — effective macro porosity
b) Permeability and fluid saturation vs. depth S_{wi} — irreducible water saturation; S_w — water saturation; S_{hy} — hydrocarbon saturation; FI_{ads} — porosity of adsorption water

2. ábra. Az algyői ALGYO–809 mélyfúrás vizsgálata
a) A kőzet térfogati összetétele a mélység függvényében
$V_{cl}*(1-p)$ — agyag; p — impermeábilis agyagmárga csíkok; $V_{si}*(1-p)$ — homokliszt; $V_{sd}*(1-p)$ — homok; $FI*(1-p)$ — effektív porozitás; $FI_{sd}*(1-p)$ — effektív makroporozitás
b) A permabilitás és a folyadéktelítettség a mélység függvényében
S_{wi} — redukálhatatlan víztelítettség; S_w — víztelítettség; S_{hy} — szénhidrogén telítettség; FI — effektív porozitás; FI_{ads} — adszorpciós porozitás

Рис. 2. Исследование скважины ALGYO–809 на месторождении Альдьё
а) Объемный состав пород как функция глубины $V_{cl}*(1-p)$ — глины; p — непроницаемые прослои глинистых мергелей; $V_{si}*(1-p)$ — алевриты; $V_{sd}*(1-p)$ — пески; $FI*(1-p)$ — эффективная пористость; $FI_{sd}*(1-p)$ — эффективная макропористость
b) Проницаемость и насыщенность жидкостями как функция глубины
S_{wi} — остаточная насыщенность водой; S_w — насыщенность водой; S_{hy} — насыщенность углеводородами; FI — эффективная пористость; FI_{ads} — адсорбционная пористость

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A SZÉNHIDROGÉN-TELÍTETTSÉG, A KŐZETÖSSZETÉTEL, A POROZITÁS ÉS A PERMEABILITÁS MEGHATÁROZÁSA SZENDVICS-KIFEJLŐDÉSŰ AGYAGOS – KŐZETLISZTES HOMOKKÖVEKBEN

BARLAI Zoltán és RÉZ Ferenc

Kifejlesztettük a szénhidrogén-tároló homokkövek egy új interpretációs rendszerét: a COMWELL–B. R./ELGI rendszert, a korábban Barlai által kidolgozott elméletre alapozva. Ezt az elméletet továbbfejlesztettük és a homokköveket az alábbi 8 komponensből összetett anyagként kezeljük: 1) impermeábilis agyagmárga csíkok a szendvics-típusú homokkőben, 2) duzzadó agyagok, 3) nem duzzadó agyagok, 4) kőzetliszt, 5) homok, 6) karbonát, 7) a vékony permeábilis kőzetcsíkok effektív porozitásával jellemezhető pórusok, 8) adszorpciós vízzel töltött pórusok.

A teljes interpretációs rendszert statisztikus alapon építettük fel az ismeretlen mennyiségek túlhatározott matematikai kezelésével. Azonban a rendszer moduláris részegységekből áll, amelyeket determinisztikus interpretációs alrendszerekbe lehet összevonni. Az alrendszerek soros kalibrálást tesznek lehetővé.

Különösen érdekes lehet a szénhidrogén-telítettség értékelésének új eljárása ebben a rendszerben, mivel a szokásos eljárások gyakran kudarcot vallanak a szendvics-kifejlődésű homokkövekben. Az elméleti és gyakorlati vonatkozásokon kívül bemutatunk egy példát egy olaj- és gáztárolót harántoló fúrás értelmezésére.

ОПРЕДЕЛЕНИЕ НАСЫЩЕННОСТИ УГЛЕВОДОРОДАМИ, СОСТАВА ПОРОД И ПРОНИЦАЕМОСТИ ТОЛЩИ С ОЧЕРЕДОВАНИЕМ ГЛИНИСТО–АЛЕВРИТИСТЫХ ПЕСЧАНИКОВ

Золтан БАРЛАИ и Ференц РЕЗ

В последние годы, на базе теории, разработанной Барлаи, нами разработана новая система интерпретации песчаниковых коллекторов нефти и газа: система COMWELL–B. R./ELGI.

Указанная теория нами усовершенствована, так что песчаники рассматриваются в качестве системы из восьми компонентов: 1) непроницаемых мергельных прослоев в толщах с очередованием глинисто–алевритистых песчаников, 2) глин набухающих, 3) глин ненабухающих, 4) алевритов, 5) песков, 6) карбонатов, 7) пор, характеризуемых эффективной пористостью в маломощных прослоях проницаемых пород, 8) пор, заполненных адсорбционной водой.

Вся система интерпретации построена на статистической основе – с переоценкой неизвестных величин при математической обработке. Сама система состоит из модульных единиц, которые могут быть объединены в детерминистские интерпретационные подсистемы. Полученные подсистемы обеспечивают возможность линейной калибровки.

В данной системе особый интерес может представлять новая методика оценки насыщенности углеводородами, поскольку обычные методики часто оказываются безпомощными в случае толщ с очередованием глинисто-алевритистых песчаников. Помимо теоретических и практических аспектов представлен пример интерпретации скважины, пройденной по коллектору нефти и газа.