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STATISTICAL INTERPRETATION TECHNIQUES FOR INCOMPLETE SET OF LOGS IN SAND-SHALE COMPLEX

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The increasing demand for data produced by quantitative well logging interpretation, especially in areas where the old and incomplete set of logs cannot be interpreted by traditional methods, has led to the elaboration of a method capable of creating synthetic logs and thus enabling a complete quantitative interpretation procedure. This method produces reliable results for well correlating areas especially in sand-shale complexes.

d: well-logging, computer programs, statistical analysis, sand-shale complexes

1. Introduction

In Hungary in recent years it has been shown that there is an increasing demand for data produced by quantitative well-logging. The applicable interpretation techniques and depending on these, the number, accuracy, and reliability of determinable reservoir-parameters depend on the set of available logs and their quality. For sandstone reservoirs in sand-shale complexes out of the three necessary porosity-indicating logs (neutron logs, density logs and transit time logs) generally only the neutron logs were available until now in Hungary.

In 1982–83 the Oil Exploration Company put into action Dresser Atlas-made well-logging equipment, a home-made acoustic-probe and a 3-parameter, hole-compensated neutron probe. The logs produced by these satisfy the interpretation demands. The neutron-probe is able to measure calibrated limestone-porosity. The reproduction capability of both methods is very good.

In the case of integrated regional interpretation of hydrocarbon reservoirs only is some recently completed wells was available the following complete set of logs

— spontaneous potential	SP,
— gamma-ray	TG,
— neutron-log	NL,
— density-log	DEL,
— acoustic log	ATL,
— laterolog deep	RLLD,
— induction deep	RILD,
— pseudo-laterolog	RPLH,
— laterolog shallow	RLLS,

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— induction medium	RILM,
— micro-laterolog	RMLL
— laterolog–8	RLL8,
— caliper log	DL

In the other wells the set logs is incomplete, even sometimes logs cannot be used for interpretation because of calibration or other errors. Generally, the following incomplete choice of logs is available:

— spontaneous potential	SP,
— gamma-ray	TG,
— neutron-log	NL,
— optimum laterolog	ROL,
— micro-laterolog	RMLL,
— caliper log	DL

Thus the well known interpretation techniques cannot be used for all wells of a given territory.

Lately, for a more exact interpretation of seismic data there is a demand for acoustic (ATL) and density (DEL) logs in each borehole, and where these parameters are lacking we must try to create them. To solve these problems a new technique was elaborated to determine parameters which cannot e calculated owing to the incomplete set of logs.

2. Elaborating the new technique

Dependig on the origin of the available data (rock physical properties *measured* on core samples, or parameters *computed* from well-logs) two different approaches should be followed.

2.1 Use of laboratory measurements on core samples

Laboratory analysis of core samples generally provides the following data and relationships:

- porosity (FILA);
- absolute permeability (KLAA);
- capillary pressure (PC) versus
  water saturation (SWLA)—PC = f(SWLA).

Knowing the hydrocarbon—water phase boundary and capillary pressure curves (PC) it is possible to work out the distribution of water saturation and residual water saturation (SWRLA) in all intervals of the reservoir, [Tóth 1972]. The results of about 1000 core sample analyses have been processed. After averaging these data on "homogeneous intervals" we gained characteristic values for 150 such intervals. *(Fig. 1)* For these we read out the corresponding values from well logs [Kiss 1972]. We then studied the connection between

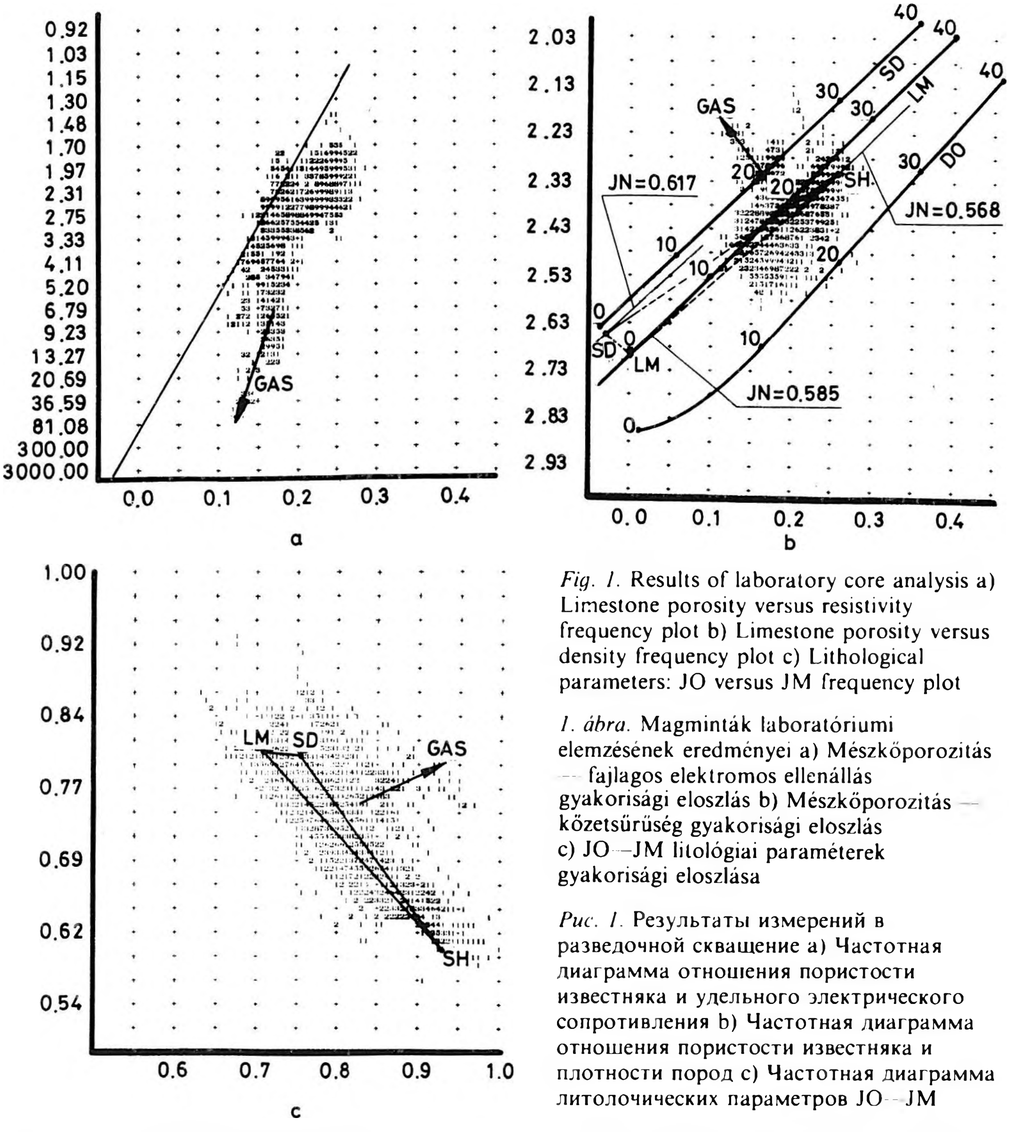

Fig. 1. Results of laboratory core analysis a) Limestone porosity versus resistivity frequency plot b) Limestone porosity versus density frequency plot c) Lithological parameters: JO versus JM frequency plot

1. ábra. Magminták laboratóriumi elemzésének eredményei a) Mészkőporozitás — fajlagos elektromos ellenállás gyakorisági eloszlás b) Mészkőporozitás — kőzetsűrűség gyakorisági eloszlás c) JO—JM litológiai paraméterek gyakorisági eloszlása

Рис. 1. Результаты измерений в разведочной скващение a) Частотная диаграмма отношения пористости известняка и удельного электрического сопротивления b) Частотная диаграмма отношения пористости известняка и плотности пород c) Частотная диаграмма литолочических параметров JO—JM

laboratory and logging data by means of multivariable regression analysis [BÁNLAKI ET AL. 1977].

$$\mathrm{FILA,\ SWLA,\ SWRLA,\ KLAA} = \mathrm{f}[(1\text{–}\mathrm{JSP}),\ \mathrm{JTG},\ \mathrm{EXP}\ (\mathrm{NG}/\mathrm{NGSH}),\ \mathrm{LN}(\mathrm{RW}/\mathrm{ROL}), \ldots] \qquad (1)$$

where
1–JSP = shale indicator (see Equ. 2a),
JTG = shale indicator (see Equ. 2b),
NG = neutron-gamma log,
NGSH = neutron-gamma intensity of shale line,
RW = resistivity of pore water.

In a given territory the reservoir parameters (FI, SW, SWR, K) were determined by the above relations leading to the following conclusions:

— As most of the cores are taken from more or less clean sandstone, core sampling is not random. The calculated parameters are reliable in such reservoir intervals;

— To extend the applicability of the method contaminated cores should also be included in the investigations.

2.2. Quantitative interpretation in one or a few boreholes

By means of joint interpretation of the logs we obtain continuous information along the borehole. The following reservoir parameters are regularly determined:

— effective porosity (FI);
— shale content (VSH);
— volume of rock matrices (VMA1, VMA2);
— water saturation in the virgin zone (SW);
— water saturation in the flushed zone (SXO);
— residual water saturation (SWR);
— permeability index (K).

Determination of shale content (VSH) takes place on the basis of "shale indicator minima", or by properly chosen shale indicators [Poupon–Gaymard 1970].

The following shale indicatos were used:

$$\mathrm{VSH1} = (1-\mathrm{JSP}) = \left(1-\frac{\mathrm{SP}}{\mathrm{SPS}}\right) \tag{2a}$$

$$\mathrm{VSH2} = (1-\mathrm{JSP})^2 \tag{2b}$$

$$\mathrm{VSH3} = \mathrm{JTG} = \frac{\mathrm{TG}-\mathrm{TGMN}}{\mathrm{TGMX}-\mathrm{TGMN}} \tag{2c}$$

$$\mathrm{VSH4} = 0.33(2^{2\mathrm{JTG}}-1) \tag{2d}$$

$$\mathrm{VSH5} = (1-\mathrm{JSP})\mathrm{JTG} \tag{2e}$$

$$\mathrm{VSH6} = \left(\frac{\mathrm{RSH}}{\mathrm{RT}}\right)^{\frac{1}{\mathrm{BRSH}}} \tag{2f}$$

$$\mathrm{VSH7} = \left(\frac{\mathrm{RSH}}{\mathrm{RT}}\cdot\frac{\mathrm{RTMX}-\mathrm{RT}}{\mathrm{RTMX}-\mathrm{RSH}}\right)^{\frac{1}{\mathrm{BRSH}}} \tag{2g}$$

where

SP = logged spontaneous potential,
SPS = static spontaneous potential,

TG = logged gamma-ray value,
TGMX = maximum value of gamma-ray log (shale-line),
TGMN = minimum value of gamma-ray log (sand-line),
RT = resistivity of the virgin zone,
RSH = resistivity of shale,
RTMX = maximum value of resistivity of the virgin zone (in pure CH reservoir),
BRSH = exponent (~ 1–2), $\mathrm{BRSH} \approx \mathrm{BM}\left(1 - \sqrt{\frac{\mathrm{RSH}}{\mathrm{RTMX}}}\right)$,
BM = cementation exponent.

Porosity and matrix volume can be calculated by solving the balance equations of rock components based on three porosity indicator logs [Schlumberger Document 1969]:

$$\mathrm{FINLM} = \mathrm{FI} \cdot \mathrm{FINF} + \mathrm{VMA1} \cdot \mathrm{FINMA1} + \mathrm{VMA2} \cdot \mathrm{FINMA2} + \mathrm{VSH} \cdot \mathrm{FINSH} \tag{3a}$$

$$\mathrm{DE} = \mathrm{FI} \cdot \mathrm{DEF} + \mathrm{VMA1} \cdot \mathrm{DEMA1} + \mathrm{VMA2} \cdot \mathrm{DEMA2} + \mathrm{VSH} \cdot \mathrm{DESH} \tag{3b}$$

$$\mathrm{AT} = \mathrm{FI} \cdot \mathrm{ATF} + \mathrm{VMA1} \cdot \mathrm{ATMA1} + \mathrm{VMA2} \cdot \mathrm{ATMA2} + \mathrm{VSH} \cdot \mathrm{ATSH} \tag{3c}$$

$$1 = \mathrm{FI} + \mathrm{VMA1} + \mathrm{VMA2} + \mathrm{VSH} \tag{3d}$$

Equation 3d is applicable as a means of control, where
FINLM = apparent limestone porosity calculated from the neutron-log,
FINMA1, FINMA2 = apparent neutron porosity of rock matrices,
DEMA1, DEMA2 = density of rock matrices,
ATMA1, ATMA2 = acoustic transit time in rock matrices,
FINSH = neutron porosity of shale,
DESH = density of shale,
ATSH = acoustic transit time in shale,
FINF = neutron porosity of pore fluid,
DEF = density of pore fluid,
ATF = acoustic transit time in pore fluid.

The equations of rock components (3a–c) contain 4 unknowns therefore shale content will independently be calculated by the earlier described shale indicators.

The matrix values (FINMA1, DEMA1, ATMA1, FINMA2, DEMA2, ATMA2), and the shale characteristics (FINSH, DESH, ATSH, RSH) can be determined on the basis of the resistivity of the virgin zone, porosity-indicators ($1/\sqrt{\mathrm{RT}} - \mathrm{FINLM}$, $1/\mathrm{RT} - \mathrm{AT}$, $1/\sqrt{\mathrm{RT}} - \mathrm{DE}$ FINLM − DE, FINLM − AT, AT − DE), and frequency plots (JN − JM, JO − JM, JO − JN) formulated by lithological parameters as JM, JN, JO (Fig, 1/a, 1/b, 1/c), where

$$JM = \frac{ATF - AT}{DE - DEF} 0.003,$$

$$JN = \frac{FINF - FINLM}{DE - DEF},$$

$$JO = \frac{FINF - FINLM}{ATF - AT} 330.$$

Plots can be used to check logs and to determine the main rock-components, because the point-set must fall on a predetermined area of the plot-field characterized by the main rock-components, e.g. sandstone (SD), limestone (LM). With the combined use of such plots we can find the faulty or incorrectly calibrated logs.

The following equations are used to calculate water saturation [POUPON ET AL. 1970, WICHTL–DRAXLER 1981]:

$$SW1 = \left[\frac{RT^{-\frac{1}{2}}}{\frac{VSH^{\left(1-\frac{VSH}{2}\right)}}{\sqrt{RSH}} + \frac{FI^{\frac{BM}{2}}}{\sqrt{BA \cdot RW}}} \right]^{\frac{2}{BN}} \qquad (4a)$$

$$SW2 = B + \sqrt{B^2 + \frac{A}{RT}} \qquad (4b)$$

where

$$A = \frac{(1 - VSH) BA \cdot RW}{FI^{BM}},$$

and

$$B = -\frac{A}{2} \cdot \frac{VSH}{RSH}$$

$$SW3 = \left[\frac{RW}{RT} \cdot \frac{BA}{FI^{BM}} \right]^{\frac{1}{BN}} \qquad (4c)$$

$$SX01 = \left[\frac{RX0^{-\frac{1}{2}}}{\frac{VSH^{\left(1-\frac{VSH}{2}\right)}}{\sqrt{RSH}} + \frac{FI^{\frac{BM}{2}}}{\sqrt{BA \cdot RMF}}} \right]^{\frac{2}{BN}} \qquad (4d)$$

$$SX02 = B + \sqrt{B^2 + \frac{A}{RX0}}$$

where

$$A = \frac{(1 - VSH) BA \cdot RMF}{FI^{BM}} \tag{4e}$$

and

$$B = -\frac{A}{2} \cdot \frac{VSH}{RSH}$$

$$SX03 = \left[\frac{RMF}{RX0} \cdot \frac{BA}{FI^{BM}}\right]^{\frac{1}{BN}} \tag{4f}$$

where

BA = tortuosity coefficient,
BM = cementation exponent,
BN = saturation exponent,
RX0 = resistivity of flushed zone,
RMF = resistivity of mud filtratum.

Two water saturation calculations are used in order to select the more favourable one from the following parameters: SW1, SW2, and SX01, SX02, respectively. The third calculation serves for the control of coefficients, like tortuosity (BA), cementation exponent (BM), and saturation exponent (BN) in pure sands.

After calculating the water saturation we correct the layer contents of the porosity indicator logs when, into equations 3a, 3b, 3c we place respectively

$$FINF^* = FINW \cdot SX0 + (1 - SX0)\, FINCH \tag{5a}$$

$$DEF^* = DEW \cdot SX0 + (1 - SX0)\, DECH \tag{5b}$$

$$ATF^* = ATW \cdot SX0 + (1 - SX0\; ATCH \tag{5c}$$

where

FINW = neutron porosity (H-index) of pore water,
DEW = density of pore water,
ATW = acoustic transit time in pore water,
FINCH = neutron porosity (H-index) of hydrocarbon,
DECH = density of hydrocarbon,
ATCH = acoustic transit time in hydrocarbon.

Next we perform an iteration procedure on equations (3a), (3b), (3c), (4a), (4b), (4d), (4e), (4f), (5a), (5b) and (5c) to improve the values of FI, VMA1, VMA2, SW and SX0 until

$FI - FI_{former} \leqq 1$—2% and

$\Delta V \leqq 5\%$ in average

where

$\Delta V = 1 - (FI + VMA1 + VMA2 + VSH)$ on the basis of Equ. (3d).

Determination of the residual water saturation is carried out from the following relationship:

$$SWR = BSWRC + BSWRM \frac{VSH}{FI} \tag{6}$$

BSWRC and BSWRM can be determined from $\frac{\mathrm{VSH}}{\mathrm{FI}}$ versus SW cross-plots. The permeability index can be calculated by the following equation:

$$K = 250\left(\frac{\mathrm{FI}^3}{\mathrm{SWR}}\right)^2. \tag{7}$$

2.3. *Creating of indicators*

Besides the konwledge of reservoir-parameters, determined from core analysis or quantitative well log interpretation other indicators derived from logs are also needed which are closely related with the reservoir-parameters. To create these indicators such logs are used which are available in all the boreholes of the area of investigation.

As indicators other values can serve as well, like

$$\mathrm{FI} = f\left\{(1-\mathrm{VSH}),\ (\mathrm{FINLM}-\mathrm{FINSH}),\ \left[\left(\frac{\mathrm{BA}\cdot\mathrm{RW}}{\mathrm{RT}} - \mathrm{VSH}\,\frac{\mathrm{BA}\cdot\mathrm{RW}}{\mathrm{RSH}}\right)(1-\mathrm{VSH})\right],\ldots\right\} \tag{8a}$$

$$\mathrm{VSH} = f\left\{(1-\mathrm{JSP}),\ \mathrm{JTG},\ \frac{\mathrm{FINLM}}{\mathrm{FINSH}},\ \left(\frac{\mathrm{RSH}}{\mathrm{RT}}\,\frac{\mathrm{RTMX}-\mathrm{RT}}{\mathrm{RTMX}-\mathrm{RSH}}\right),\ldots\right\} \tag{8b}$$

$$\mathrm{SW},\ \mathrm{SX0} = f\left\{\left(\frac{\mathrm{RX0}}{\mathrm{RMF}}\,\frac{\mathrm{RW}}{\mathrm{RT}}\right),\ \frac{\mathrm{FI}}{\mathrm{FIMX}},\ \left[\frac{\mathrm{RT}}{\mathrm{BA}\cdot\mathrm{RW}}(\mathrm{FINLM}-\mathrm{FINSH})\right],\ (1-\mathrm{VSH}),\ldots\right\} \tag{8c}$$

Determination of SWR and K takes place in the same manner as described in Section 2.2.

Next we must find the optimum relationship between reservoir parameters and indicator values to enable us to ensure the determination of reservoir parameters in the other boreholes of the territory.

3. Determination of relationships between reservoir parameters and indicators, computation of reservoir parameters

In order to solve this problem it was necessary to develop a so called statistical indicator system program (SIP) which functions as a subsystem of the well logging interpretation system (KISS).

3.1. Determination of relationships

Main steps:
- — calculation of indicator values for the entire investigated interval,
- — determination of partial correlation coefficients between reservoir parameters and indicators,
- — selection of indicators showing a good correlation with a view to improving the total correlation coefficient,
- — determination of relationships between indicators and reservoir parameters on the basis of multivariate linear regression,
- — calculation of total correlation coefficient for checking purposes [VINCZE 1975].

When making the primary choice of indicators the value of the partial correlation coefficient is decisive because an indicator with larger partial correlation improves the total correlation. (Among the chosen indicators there is no need for those with weak partial correlation). In spite of their relatively high partial correlation among the chosen indicators those which do not improve the value of the total correlation will also be eliminated.

This method must be used for determining all reservoir parameters. If the relationship is not good enough regarding the total correlation coefficient, it is necessary to find further indicators to improve this relationship.

3.2 Calculation of reservoir parameters

Relationships determining the reservoir parameters and the indicator values form a phase of a computational subsystem of the KISS-system. In the other boreholes of the area of investigation calculation of reservoir parameters are carried out in this phase. Indicator systems and coefficients of different investigation areas form a phase of the above mentioned subsystem. *Table I* shows the determined parameters and their total correlation coefficient for one of the investigated areas.

Table I

Reservoir parameter	Abbreviation	Total correlation coefficient
Effective porosity	FI	0.972
Shale content	VSH	0.993
Volume of matrix No 1	VMA1	0.868
Volume of matrix No 2	VMA2	0.759
Water saturation	SW	0.95
Water saturation of flushed zone	SX0	0.913
Residual water saturation	SWR	0.956

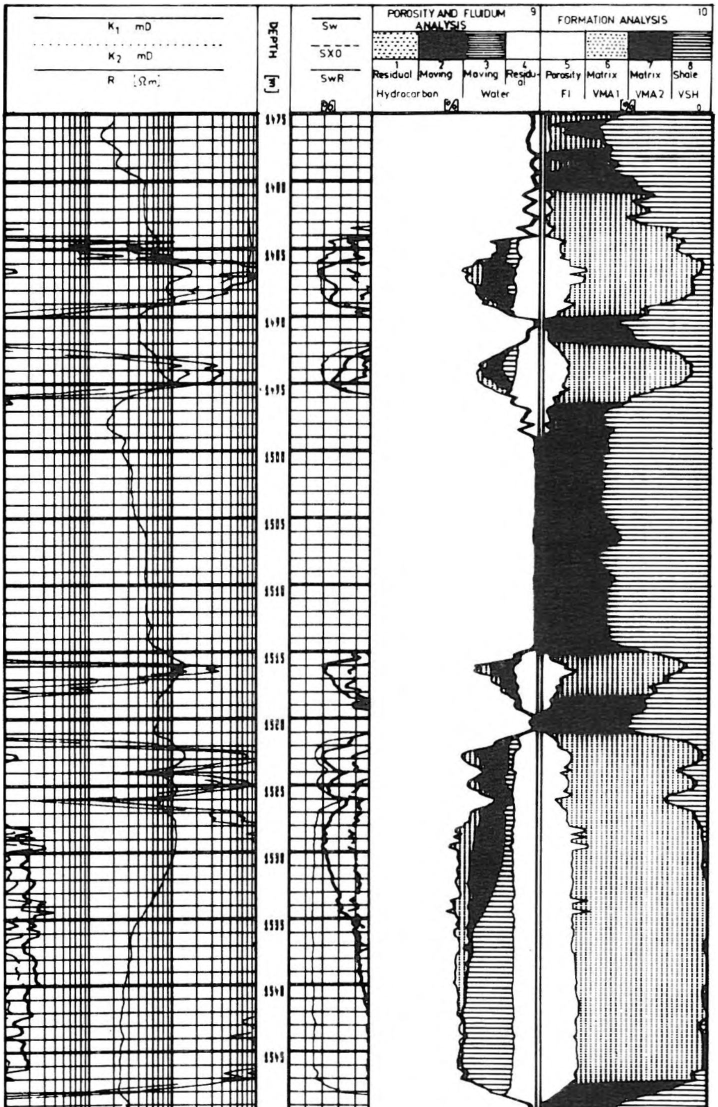

Table I shows that the total correlation coefficient is greater than 0.9, except for the two matrix volumes. Relationships thus seem good enough except for the two used for the volumes. Since these do not really belong to the reservoir parameters we omit their calculation.

Using the relationships for boreholes KIS-3 and KIS-38 of the investigated area, *Figs 2 and 3* present the results of the interpretation obtained by the SIP program.

Fig. 2. Results of quantitative well logging interpretation
K_1, K_2 — permeability indices; R — resistivity log; SW — water saturation in the virgin zone; SX0 — water saturation in the flushed zone; SWR — residual water saturation

2. ábra. A komplex kvantitatív karotázs interpretáció eredményszelvénye
K_1, K_2 — permeabilitás indexek; R — ellenállás szelvény; SW — víztelítettség az érintetlen zónában; SX0 — víztelítettség a kisepert zónában, SWR — maradék víztelítettség; 1 — maradék szénhidrogén térfogat; 2 — mozgó szénhidrogén térfogat; 3 — mozgó víz térfogat; 4 — maradék víz térfogat; 5 — effektív porozitás; 6 — 1. mátrixtérfogat (homok); 7 — 2. mátrixtérfogat (mészkő); 8 — agyagtartalom; 9 — porozitás és rétegtartalom elemzés; 10 — formáció elemzés

Рис. 2. Результаты комплексной количественной интерпретации каротажных данных
K_1, K_2 — индексы проницаемости; R — кривая сопротивления; SW — водонасыщенность в ненарушенной зоне; SX0 — водонасыщенность в промытой зоне; SWR — остаточная водонасыщенность; 1 — остаточный объем углеводородов; 2 — подвижный объем углеводородов; 3 — подвижхый объем воды; 4 — остаточный объем воды; 5 — эффэктивная пористость; 6 — объем вмещающей породы 1 (песок); 7 — объем вмещающей породы 2 (известняк); 8 — содержание глины; 9 — анализ пористости и содержания пласта; 10 — анализ формации

3.3 Generation of synthetic logs

As in the case of the reservoir parameters, synthetic logs can also be created. This method basically corresponds with the described one, but instead of reservoir parameters it needs well calibrated logs of the type to be synthetized measured in some of the boreholes of the study area. As a means of solving seismic interpretation tasks the demand has arisen for acoustic and density logs. The left side of *Fig. 4* shows the calculated and measured density (DE) logs; on the right side is situated the result of statistical quantitative interpretation. (N.B. The logged density curve did not serve as a basic parameter for creating the relationship, but we used it for checking purposes only.) It can be seen that the measured log corresponds well with the synthetic log (deviation 0.05 g/cm^3). Deviation is greater in hydrocarbon bearing intervals, but if we use reservoir parameters to create indicators, the accuracy can be increased by iteration.

4. Conclusions

The method discussed is expected to give reliable results in geologically well correlatable regions, first of all in sandstone formations. One of its advantage, that it can transform the old, incompletely logged well data into a set that is already suitable for a complex, quantitative well-log interpretation. Missing, or poor quality logs can be replaced, at a later date, by synthetic logs computed by the proposed method, and these synthetic logs can be subjected, together with the „real" ones, to a regional processing.

The accuracy of log synthetization can be improved by iteration if reservoir parameters are included into the indicator system.

The method can be used for filtering of measured logs—as verified in the course of log synthetization—i.e. filtering can be used in the first phase of data processing.

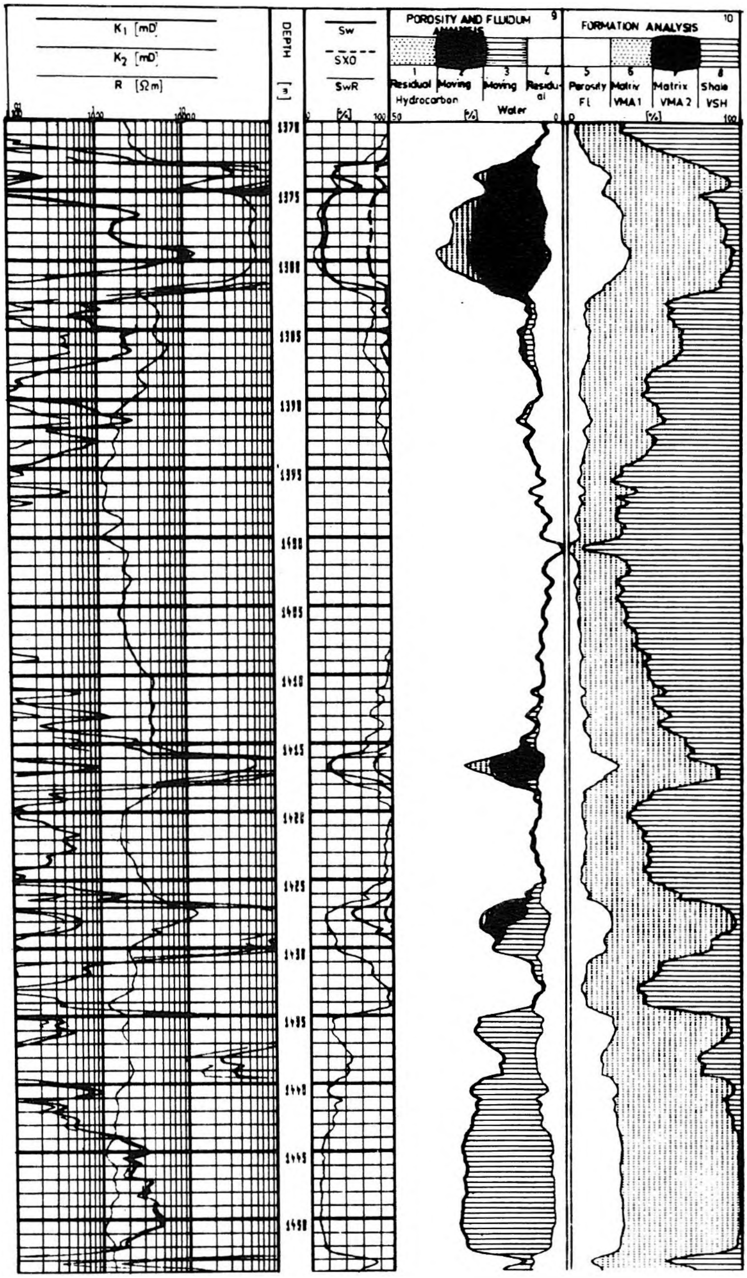

Fig. 3. Results of quantitative interpretation by the statistical program SIP. Legend as in Fig. 2.

3. ábra. Statisztikus módszerrel készült kvantitatív karotázs interpretáció (magyarázatok a 2. ábrán)

Рис. 3. Количественная интерпретация данных каротажа по статистическому методу. (Объяснения даны на Рис. 2)

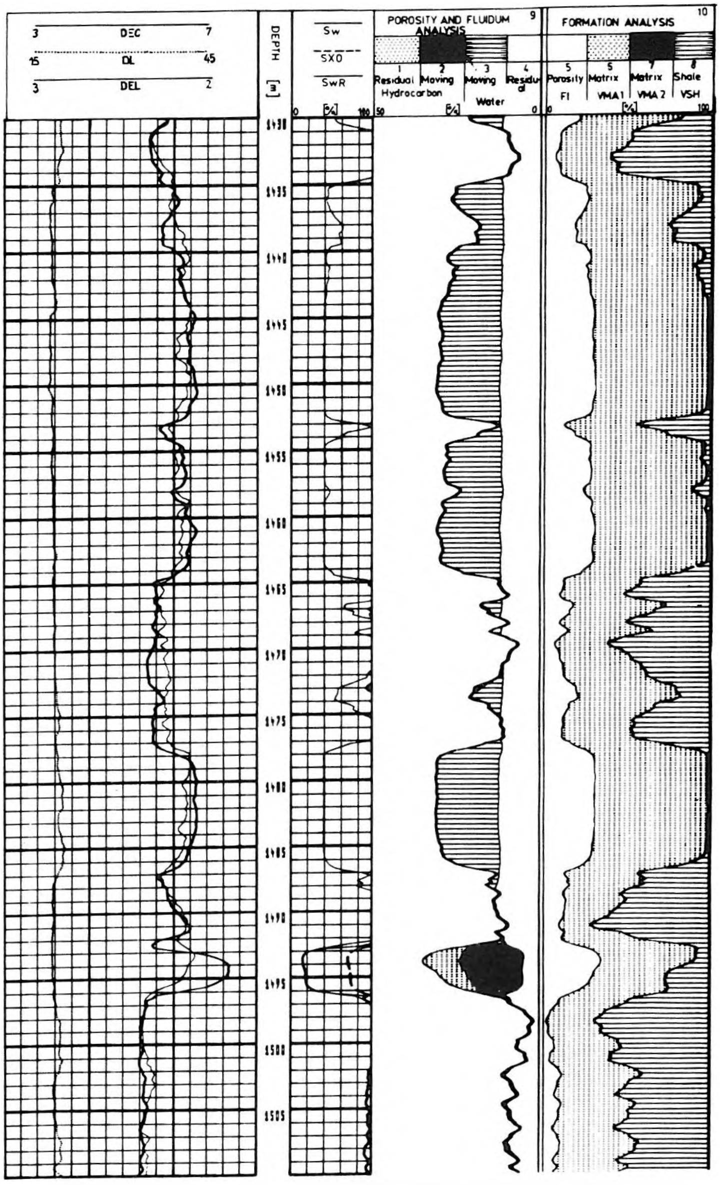

Fig. 4. Comparison of synthetic density log with a measured one
DEL — measured density log; DEC — synthetic density log; DL — caliper log. Legend as in Fig. 2

4. ábra. Szintetikus sűrűség szelvény összehasonlítása a fúrólyukban mért szelvénnyel
DEL — mért sűrűségszelvény; DEC — számított sűrűségszelvény; DL — lyukátmérő szelvény; (további magyarázatok a 2. ábrán)

Рис. 4. Сопоставление синтетической диаграммы плотности с измеренной в скважине диаграммой
DEL — измеренная кривая плотности; DEC — расчетная кривая плотности;

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STATISZTIKUS ÉRTELMEZÉSI ELJÁRÁSOK ALKALMAZÁSA AGYAGOS HOMOKKŐ TÁROLÓKBAN, HIÁNYOS SZELVÉNYVÁLASZTÉK ESETÉN

KISS BERTALAN, KORMOS LÁSZLÓ

Az utóbbi években egyre nagyobb igény mutatkozik a kvantitatív karotázs interpretáció által szolgáltatott adatok iránt olyan területeken is, ahol a nagyobbrészt régen készült, hiányos szelvényválaszték — az ismert módszerekkel — ezt nem teszi lehetővé.

Az alábbiakban vázolt eljárással lehetővé válik egy eltérően — hiányosan — szelvényezett kutatási terület hasonló módon és hasonló minőségben történő mélyfúrási geofizikai feldolgozása. Előállíthatók — utólagosan — szintetikus szelvények, melyeknek a fúrólyukban történő felvételére már nincs mód.

A módszer geológiailag jól korrelálható területeken, elsősorban homokos-agyagos formációkban szolgáltat megbízható eredményt.

ПРИМЕНЕНИЕ СТАТУСТИЧЕСКИХ МЕТОДОВ ИНТЕРПРЕТАЦИИ ДЛЯ ПЕСЧАНО-ГЛИНИСТЫХ КОЛЛЕКТОРОВ В СЛУЧАЕ НЕПОЛНОЙ КОМПЛЕКТНОСТИ КАРОТАЖНЫХ КРИВЫХ

Б. КИШ, Л. КОРМОШ

За последнее время увеличивающийся спрос предъявляется к результатам количественной интерпретации каротажных данных, хотя эти требования не всегда могут быть удовлетворены с применением известных методов, в связи с некомплектностью имеющихся каротажных кривых.

В работе предлагается метод, дающий достоверные результаты в геологически хорошо коррелируемых районах, в первую очеред в песчано-глинистых формациях. Вместо отсутствующих видов каротажных кривых, которые уже нельзя получить в скважинах, можно создать расчетные синтетические кривые.

Предлагаемый метод позволяет проводить достоверную обработку каротажных данных в районах, недостаточно изученных промыслово-геофизическими методами.