Formation Evaluation by Multidimensional Petrophysical Correlations in Azerbaijan

Alexander Rutman and Haim Fligelman
Petroleum Infrastructure Corporation Ltd. Israel

ABSTRACT

A multidimensional petrophysical correlation method for improving logging data interpretation was developed and applied on some oil and gas fields in Azerbaijan. This project utilized both petrophysical and core data from the upper three horizons of the Productivnaja Tolshcha formation, a series of unconsolidated sands, clays and sandstones of Neogene age between the depths of 1500 to 2000 meters. The reservoirs in this formation are characterized by porosity values of 18 to 30% and permeablilties of 20 to 800 md.

The suggested statistical method is based on constructed multidimensional correlations between directly measured well geophysical characteristics of rocks, and the actual formation rock properties including porosity, permeability and clay content, all of which were measured in the laboratory on about 500 recovered cores. The effect of formation temperature and pressure on the reservoir rock properties was also considered in the correlations.

The geophysical well log data were generally taken from a suite of logs including several electric resistivity devices with different radii of investigation, spontaneous potential (SP), gamma-ray, neutron and caliper. Special statistical criteria were used to estimate the representativity of the core data in cases of low percentage core recovery.

Multidimensional statistical correlations were prepared using regression analysis and presented in the form of algerbraic polynomials. Coefficients of the polynomials were calculated by the least squares method. The accuracy of the polynomials was measured by correlation coefficients. A comparison of the formation evaluation results obtained by multidimensional polynomials, with that obtained from core data in different petroleum reservoirs in several Azerbaijan fields is presented. Results of this comparison show that there is good agreement between the real and computer-derived data.

This correlation method effectively supplements the minimal geophysical logging data of many of the early wells of the Kura River region's oil and gas fields, and improves the well log interpretation.

INTRODUCTION

Formation evaluation by well logging data is based on empirical correlations between directly measured well geophysical characteristics of rocks, and their actual physical properties, such as porosity, permeability and clay content. Because of the numerous factors affecting reservoir rock properties, many of which are not taken into consideration in well logging interpretation, and any petrophysical correlations are stochastic in nature.

The petroleum industry made considerable progress in resolving the major part of this problem by using a suite of geophysical logs simultaneously. Particularly important are the class of logs usually known as porosity logs (i.e., acoustic, density and neutron) along with log-derived clay content indicators, (i.e., spontaneous-potential and gamma-ray). This suite often provides a detailed and relatively precise analysis of the subsurface rock composition in terms of porosity, percentages of the main mineral constituents of the matrix and shale content. This method is particularly useful when the reservoir is a shaly sand.

Unfortunately, most of the well logs from the Azerbaijan fields are of the earliest types, and include many that date back to the introduction of the first logs and equipment. Many older Azerbaijan oil fields and even some of the relatively new ones were surveyed without any porosity log, and hence, their interpretation was necessarily based on qualitative porosity data. Because of this situation, a statistical technique was sought that would be suitable for the specific region.

The goal of this investigation was the development of multidimensional petrophysical correlations for the lithological interpretation of geophysical logs in oil and gas fields in Azerbaijan primarily where modern and reliable reservoir data are lacking.

DESCRIPTION OF THE STATISTICAL METHOD

Multidimensional statistical petrophysical models generally relate laboratory measurements of formation properties (Y_{mi}) with geophysical log parameters $(X_1..X_n)_i$:

$$Y_{mi} = F(X_1, X_2, \dots X_n) \qquad (1)$$

Based on multidimensional regression analysis, correlations were presented in the form of the most common linear model of algebraic polynomials (Rutman and Ellansky, 1967b). Because these polynomials should be competent with all the data points, a special statistical procedure for choosing the suitable polynomial was used. All petrophysical data of formation rock properties (Y_{mi}) and geophysical logging parameters (X_i) were divided into two parts. Each part of the data was sampled from the whole petrophysical data according to a table of random numbers, and hence all parameters of X and Y had equal probability to be sampled. Based on the first part of the data, the various formation rock properties were approximated by appropriate polynomials:

$$P(X) = C_0 + C_1X_1 + C_2X_2 + \ldots + C_nX_n \tag{2}$$

The coefficients C_0, $C_1 \ldots C_n$ were determined by the least squares method (Van der Waerden, 1960), which requires:

$$g(C_o, C_1, C_2 \ldots C_n) = [P(X_i) - F(X_i)]^2 = \min \ldots \tag{3}$$

By means of the developed polynomials, Y values were calculated for each formation rock property (Y_{ci}). The statistical variance S_1^2 of this set of data was calculated as well :

$$S_1^2 = \frac{\sum_{i=1}^{N_1} \Delta Y_i^2}{N_1 - m} \tag{4}$$

where:

Y_{ci} – calculated value of Y.

Y_{mi} – measured value of Y.

ΔY_i – difference between the calculated and measured values of Y, ($Y_{ci} - Y_{mi}$).

N_1 – number of data points of the first sampling.

m – number of polynomial coefficients.

The accuracy and the degree of association between the variables of each polynomial were measured by the sample correlation coefficient r:

$$r = \sqrt{1 - \frac{S_1^2}{S_0^2}} \tag{5}$$

where: S_0^2 is:

$$S_0^2 = \frac{\sum_{i=1}^{N_1} (Y_{mi} - Y_m)^2}{N_1 - 1} \tag{6}$$

and $\bar{Y}_m$ is the arithmetic mean of Y_{mi} .

The accuracy of the relation could also be measured by a second statistical parameter, θ, which was defined (Neiman, 1986) as:

$$\Theta = \sqrt{\frac{1}{1-r^2}} \tag{7}$$

In the next stage of the procedure, each developed polynomial was validated by the second part of the data (second sampling). By applying the polynomials to the second set of data, a new statistical variance value S_2^2 was calculated:

$$S_2^2 = \frac{\sum_{i=1}^{N_2} \Delta y_i^2}{N_2} \tag{8}$$

where:

N_2 – number of data points of the second sampling,

ΔY_i – the same as defined in Eq. (4), but related to the second sampling.

By this procedure various polynomials for each formation property were obtained. Fisher criterion (Van der Waerden, 1960) was then used to select the most suitable one. This criterion requires that the variance value of both samplings, S_1^2 and S_2^2, will not differ significantly. If by applying this criterion several polynomials had practically equal effectiveness, then the simplest polynomial form with the least number of independent variables involved was preferred.

Another statistical criterion which was calculated for each parameter (X_i) of a constructed polynomial, was M_i :

$$M_i = \frac{|C_i| X_i}{C_0 + \sum_{i=1}^{m} |C_i| X_i} \tag{9}$$

where $\bar{X}_i$ – is the arithmetic mean of X_i values, and M_i reflects the contribution of each independent variable to the required information.
The best multidimensional statistical correlations are those which include the largest value of θ and have variables X_i with the largest values of M_i.

The errors ($S_{\bar{F}_P}$) involved in any of the suitable multivariable petrophysical correlations were likely caused either by inaccurate core measurements in the laboratory, inaccurate logging data caused by the constraints of the logging tools and bad borehole conditions, or by the mathematical approximations themselves.

These errors were quantified for the average values of any formation rock property characteristic by:

$$S_{\bar{F}_p} = \sqrt{S_{\bar{F}_c}^2 + S_{\bar{F}_g}^2} \tag{10}$$

where:

$S_{\bar{F}_c}$, $S_{\bar{F}_g}$ - quadratic mean error of the average value of a formation rock property F, calculated from cores and logs, respectively.

$S_{\bar{F}_c}$ could be calculated according to the equation:

$$S_{\bar{F}_c} = \frac{S_{F_c}}{\sqrt{n}} \tag{11}$$

Where S_{F_c} is the standard deviation of formation rock property for a given number of samples:

$$S_{F_c} = \sqrt{\frac{\sum_{i=1}^{n}(F_{ci} - \bar{F}_c)^2}{n-1}} \tag{12}$$

and:

n - number of core samples

F_{ci} - formation rock property measured from each core sample

$\bar{F}_c$ - arithmetic mean of measured formation rock property

Using $S_{\bar{F}_p}$ estimated from the correlation coefficient, and S_{F_c} calculated from Eq. 11, the geophysical logging error was approximated according to

$$S_{\bar{F}_g} = \sqrt{S_{\bar{F}_p}^2 - S_{\bar{F}_c}^2} \tag{13}$$

THE APPLIED STATISTICAL - PETROPHYSICAL DATA

The statistical method, outlined in the previous chapter, was applied to petrophysical data from three upper horizons of the Neogene-aged Productivnaja Tolshcha formation (hereafter, PT Fm.), in Azerbaijan. This formation occurs in the well-known oil fields, Kurovdag, Mishovdag, Kalmas and Kursangja, that are located in the region of the Kura River (Fig. 1). These upper three horizons are encountered at depths between 1500 to 2000 meters, and are made up of unconsolidated sands and alternating sandstones and clays. Generally the sand reservoirs are characterized by porosity values ranging from 18 to 30% and by permeablility values ranging from 20 to 800 md. These data were obtained from about 500 cores recovered from these fields (Adjalova, 1962).

As mentioned earlier, the suite of the well logs in these fields were of the "old type" and typically included several electric resistivity devices with different radii of investigation, spontaneous potential (SP), gamma-ray, neutron and caliper. However, the neutron log (given in IMP/min) wasn't used as a porosity device. From these logs the following general data were noted:

1. resistivity of the rocks ranges widely from 2 to 40 ohm-m depending on the lithology type and fluids saturating the rock;
2. resistivity of the clays has the same magnitude as that of the water-bearing beds (2-4 ohm-m);
3. the SP is a good shale indicator and easily detects sand-clay alternations. The shale base line is stable and easily determined;
4. formation water resistivity in the oil fields ranges between 0.06 to 0.29 ohm-m; and
5. mud filtrate resistivity at formation temperature ranges from 0.5 to 2.8 ohm-m.

The sand-shale alternating layers are also easily detected on the gamma-ray and neutron logs. The good quality of these logs facilitated a reliable analysis.

The similarity in lithology, petrography and logging characteristics of the reservoir rocks of the PT Fm. enabled the statistical anlysis to treat all the petrophysical information as one represtative input data. The petrophysical data were distributed normally or lognormally (in the case of permeability).

Figures 2 and 3 present frequency distribution curves of clay content and natural gamma-ray radioactivity for different samples sizes. These groups were sampled from all petrophysical data by random numbers, and thus, each data point had equal probability to be included in the sampling. As also shown, these formation properties have almost normal distribution and for practical purposes the number of data points do not affect the distribution curves. A similar investigation was made for the other petrophysical parameters, and its results regarding the number of data points, were similar. Thus it was concluded that the developed petrophysical correlations method would be useful for the entire region (Rutman and Burjakovskaja, 1966).

The petrophysical correlations were based on the following parameters:

a. Fundamental formation properties measured in the laboratory on recovered cores: namely, effective porosity (ϕ) in percent, absolute horizontal permeability (k) in millidarcies, and clay content (C) in percent. The clay content actually expressed the percentage of the grain sizes less than 0.01 mm in the total weight of the sample. The clay content was quantified also by the q parameter:

$$q = \frac{(1 - \phi)C}{(1 - \phi)C + \phi} \tag{14}$$

where in this case ϕ and C are given in fractions. Here q represents the fraction of space (clay plus fluid) occupied by clay.

The final laboratory parameter which was considered in the study was the formation resistivity factor (F):

$$F = \frac{R_o}{R_w} \tag{15}$$

where:

R_o – resistivity of water-saturated rock.
R_w – resistivity of formation water.

b. Direct geophysical log measurements:

1. R_i – resistivity of the invaded zone measured by the inverted short lateral log (N 0.1 M 0.5 A);
2. R_{mf} – resistivity of mud filtrate at formation temperature;
3. E_{sp} – borehole-recorded spontaneous potential;
4. d_h – diameter of the borehole opposite the measured bed;
5. T_f – formation temperature; and
6. D – depth of the bed which reflects also formation pressure.

Thus, parameters T_f and D contain information concerning formation rock conditions.

c. Logging dimensionless values as a function of depth, calculated from direct measurements of the logging devices:

1. F_z – formation resistivity factor, calculated by the resistivity of the invaded zone (R_i), the resistivity of the mud filtrate (R_{mf}) and the residual oil saturation (S_{or}):

$$F_z = \frac{R_i(1-S_{or})^2}{R_{mf}} \tag{16}$$

2. α_{SP} – SP shaliness factor which indicates the degree of bed shaliness either laminated or disseminated, and is defined as:

$$\alpha_{SP} = \frac{E_{SP}}{E_{SP,max}} \tag{17}$$

where $E_{SP,max}$ – maximum deflection of the SP curve, when positioned opposite a "clean sand".

3. J_n – neutron shaliness factor which is defined as:

$$J_n = \frac{N_f}{N_{cl}} \tag{18}$$

where N_f – Neutron log response opposite the measured bed, and
N_{cl} – neutron log response opposite bed containing 100% clay.

4. J – gamma-ray shaliness factor (in percent) which is related to the clay content and is expressed by:

$$J = \frac{GR_{max} - GR}{GR_{max}} \cdot 100 \tag{19}$$

where GR – gamma-ray log response opposite the bed and
GR_{max} – gamma-ray log response opposite bed containing 100% clay.
This factor is equal to $1-V_{cl}$ where V_{cl} is the well known parameter of clay volume, assuming also that the gamma-ray response in clean sand is negligible.

The use of dimensionless groups can also be used to eliminate undesired environmental effects on the correlations, such as, borehole geometry, invasion, design of the logging tool, etc.

RESULTS OF THE INVESTIGATION

In the first stage of the investigation the relationships between the various formation rock properties and the dependence of each formation rock property with one geophysical log measurement (paired correlation) were studied.

Table 1 presents the relations between the various reservoir rock properties. As shown, all the correlations directly relate to the physical observations. These resultant equations can be used to calculate permeability not obtainable from cores, or to supply other missing petrophysical core data by knowing the other parameters. Equations 3 and 4 show that the permeability was better correlated with clay content parameter q than with C. An increase of both values q and C causes a decrease in permeability and porosity. Equations 6 and 8 show that porosity is better related to C and formation depth D, than to the clay content by itself.

The main purpose of developing paired correlations was to be able perform a sensitivity analysis for the effect of the individual parameter on the dependent value. Its results were considered in the next stage of the investigation which deals with multidimensional correlations.

Two types of paired correlations between formation rock properties and geophysical log measurements were developed (Tables 2 and 3):

1. "natural" relations in which each log response was considered to be a function of only one formation property, and
2. "inverse" relations in which the geophysical log parameter was considered as the argument, and the dependent variable as one of the formation rock properties. These correlations are required for the calculation of formation rock properties from logging data.

Equations 1 through 8 in Table 2 show the effect of porosity, permeability and clay content on the responses of self-potential, gamma ray and neutron logs. From these observations formation properties can be correlated with SP (or α_{SP}), J and J_n as shown in Table 3.

Equation 11 in Table 2 represents the dependence of the formation factor as derived from resistivity logs on the porosity and q parameter. Equations 9 and 10 correlate the formation factor measured in the laboratory with the same parameters. As shown, the latter correlations are significantly better. This fact is shown as well in the inverse correlations between porosity and formation factor (Eq. 1 and 2, and Table 3).

Equations 2, 3 and 11 in Table 2 and equations 2,3,4,5 and 8 in Table 3 indicate clearly the poor correlations found between F_Z and α_{SP}, and the formation rock properties. The original geophysical log measurements from which those dimensionless groups were calculated are correlated better using formation rock properties. A possible explanation may be that the α_{SP} values were incorrectly calculated because the "picked clean" sand value was in error. The calculated F_Z values also contained some apparent errors in which the assumed saturation for the residual oil was questionable.

Equations 2 through 5 in Table 2, and equations 10 through 14 in Table 3 present paired correlations between permeability and log data. As shown, the obtained correlations were very poor (θ equal to 1.04–1.11), and therefore, it was concluded that permeability cannot be estimated by only one log.

However, a good correlation was noted between SP log response and clay content (equation 3 in Table 2 and Eq. 15–16 in Table 3). For the cases in which the clay content reaches more than about 35%, the above relations fail, and gamma-ray clay content relations must be applied.

As previouly mentioned, the next stage of the investigation dealt with the main purpose of developing multivariable correlations between formation rock properties and geophysical log charateristics. Based on a maximum of nine selected parameters, the general formulation of those correlations were as follows:

$$Y = f(R_i/R_{mf},\ E_{SP},\ \alpha_{SP},\ F_z,\ J,\ J_n,\ D,\ T_f,\ d_h) \qquad (20)$$

The correlations were developed for three formation rock properties: porosity, permeability and clay content (C or q). In some of the cases the correlations were developed by utilizing natural logarithms of the X_i and Y_i values. More than one hundred multidimensional correlations were developed, and using statistical criteria, the most suitable ones with the simplest forms and the largest coefficients θ were selected (Table 4). The various coefficients of the correlations have different dimensions, depending on the units of the logs' response. As with paired correlations, better multidimensional correlations were derived using the original geophysical log measurements of R_i, and E_{SP} rather than the dimensionless groups of F_Z and α_{SP}.

The development of the correlations was done using a computer program and their integration in a computer-processed log analysis is shown on the flow chart in Fig. 4. Fig. 5 presents a comparison between porosity values measured from cores, and porosity values calculated by the correlation method (Eq. 3, Table 4). The correlation method's results are in good agreement with the core data.

The errors involved in calculating average formation rock properties from core data, for instance $\ln(\phi)$ from Eq. 3 and $\ln(k)$ from Eq. 9 in Table 4 were:

$$S_{(l\bar{n}\phi)_c} = 0.12 \quad \text{and} \quad S_{(l\bar{n}k)_c} = 0.50.$$

As the estimated errors of the above values from the correlations were

$$S_{(l\bar{n}\phi)_p} = 0.15 \quad \text{and} \quad S_{(l\bar{n}k)_p} = 0.95.$$

then the errors involved in logging data were (Eq. 13)

$S_{(l\bar{n}\phi)_g} = 0.09$ and $S_{(l\bar{n}k)_g} = 0.81$.

As shown above, the errors of the correlation method were affected mainly by geophysical logging errors.

CONCLUSIONS

The main conclusions of this study are:

1. A statistical approach of developing multidimensional correlations between rock formation properties obtained from core data and geophysical well log data is presented, and was used to improve the quantitative interpretation of old and minimal well logging data from the Productivnaja Tolshcha Fm. in the Kura River region. Although this approach was designed to be of general application and not restricted to any geographical area, the developed correlations are useful only for the well logs of the Kura River region.
2. Using the statistical procedure outlined, the correlations could be applied to an extensive region after verifying that the physical properties of a correlative formation encountered in several oil fields are normally distributed, and the number of samples do not affect the distribution curve. This examination should be the first phase of the statistical analysis.
3. In an attempt to eliminate environmental effects, it was tried to correlate between formation rock properties and some dimensionless groups calculated from logging measurements. Because the calculations of these groups were based on assumptions some of which proved to be questionable, better correlations were developed using actual geophysical well logging data.
4. By including formation depth which is correlated to temperature and pressure, the quality of the developed multidimensonal correlations was improved.
5. A new statistical approach for estimating errors involved in logging data is also presented.

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NOMENCLATURE

C - clay content, [%].

C_i - polinomial coefficient.

D - depth of bed, [m].

d_h - borehole diameter, [cm].

E_{SP} - borehole-recorded spontaneous potential, [mV].

$E_{SP,max}$ - maximum deflection of the SP log when positioned opposite a "clean sand".

F - formation resistivity factor measured in the laboratory.

F_{ci} - formation rock property measured from each core sample.

$\bar{F}_c$ - arithmetic mean of measured formation rock property.

F_z - formation resistivity factor calculated by logging the invaded zone.

GR - gamma-ray log response opposite the formation, [IMP/min].

GR_{max} - gamma-ray log response opposite bed containing 100% clay, [IMP/min].

J - gamma-ray shaliness factor.

J_n - neutron shaliness factor.

k - permeability, [md.].

M_i - statistical criterion.

m - number of polynomial coefficients.

N_1 ,N_2 - number of data points of first and second sampling.

n - number of core samples.

N_f - neutron log response opposite the measured bed, [IMP/min].

N_{cl} - neutron log response opposite bed containing 100% clay, [IMP/min].

r - sample correlation coefficient.

q - fraction of the clay-fluid space occupied by clay.

R_i - resistivity of invaded zone, [ohm-m].

R_{mf} - resistivity of mud filtrate, [ohm-m].

R_o - resistivity of water saturated rock. [ohm-m].

R_w - resistivity of formation water, [ohm-m].

S_1, S_2 - variance values of the first and second sampling, respectively.

$S_{\bar{F}_p}$ - quadratic mean error of evaluation of average formation properties by statistical petrophysical polynomial.

$S_{\bar{F}_c}$, $S_{\bar{F}_g}$ - quadratic mean errors of the average value of a formation property calculated from cores and logs, respectively.

T_f - formation temperature [^oC].

X - dependent variable of the statistical petrophysical correlation.

Y - independent variable of the statistical petrophysical correlation.

Y_c - calculated value of Y.

Y_m - measured value of Y.

α_{SP} - shaliness correction factor calculated from the SP log.

ϕ - effective porosity, %.

θ - Neiman coefficient.

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TABLE 1: CORRELATIONS BETWEEN VARIOUS FORMATION PROPERTIES

NO.	Equation	r	θ
1	$\ln k = 23.3 + 29.1\ln C - 9.3(\ln C)^2 + 0.9(\ln C)^3$	0.71	1.42
2	$\ln k = 3.72 - 5.09\ln\phi + 1.69(\ln\phi)^2$	0.73	1.46
3	$\ln k = -1.01 + 0.26\phi - 5.02q$	0.80	1.67
4	$\ln k = -1.46 + 0.25\phi - 0.004C$	0.73	1.46
5	$\ln k = 4.25 + 0.25\phi - 5.18q - 0.63\ln D$	0.87	2.03
6	$\ln\phi = 3.16 + 0.24\ln C - 0.09(\ln C)^2$	0.53	1.18
7	$\ln\phi = 2.26 + 0.29\ln k - 0.024(\ln k)^2$	0.78	1.60
8	$\phi = 28.7 - 0.12C - 0.0023D$	0.72	1.44

TABLE 2: "NATURAL" CORRELATIONS BETWEEN ONE LOG DATA AND FORMATION PROPERTY

NO.	Equation	r	θ
1	$E_{SP} = -4.62 + 1.03\phi$	0.62	1.27
2	$E_{SP} = 14.64 + 0.02k$	0.40	1.09
3	$E_{SP} = 36.8 - 43.8q$	0.80	1.67
4	$J = 4.07 + 0.72\phi$	0.27	1.04
5	$J = 16.27 + 0.02k$	0.28	1.04
6	$J = 70.8 - 0.68\phi - 83.8q$	0.67	1.35
7	$J_n = 1.47 - 0.51q$	0.36	1.07
8	$J_n = 2.1 - 0.02\phi - 1.2q$	0.48	1.12
9	$\ln F = 5.79 - 1.04\ln\phi$	0.83	1.79
10	$\ln F = 6.54 - 1.20\ln\phi - 0.6q$	0.87	2.03
11	$\ln F_Z = 5.79 - 0.91\ln\phi - 2.16q$	0.51	1.16

TABLE 3: INVERSE PAIR" CORRELATIONS BETWEEN ONE LOG PARAMETER AND FORM ATION PROPERTY

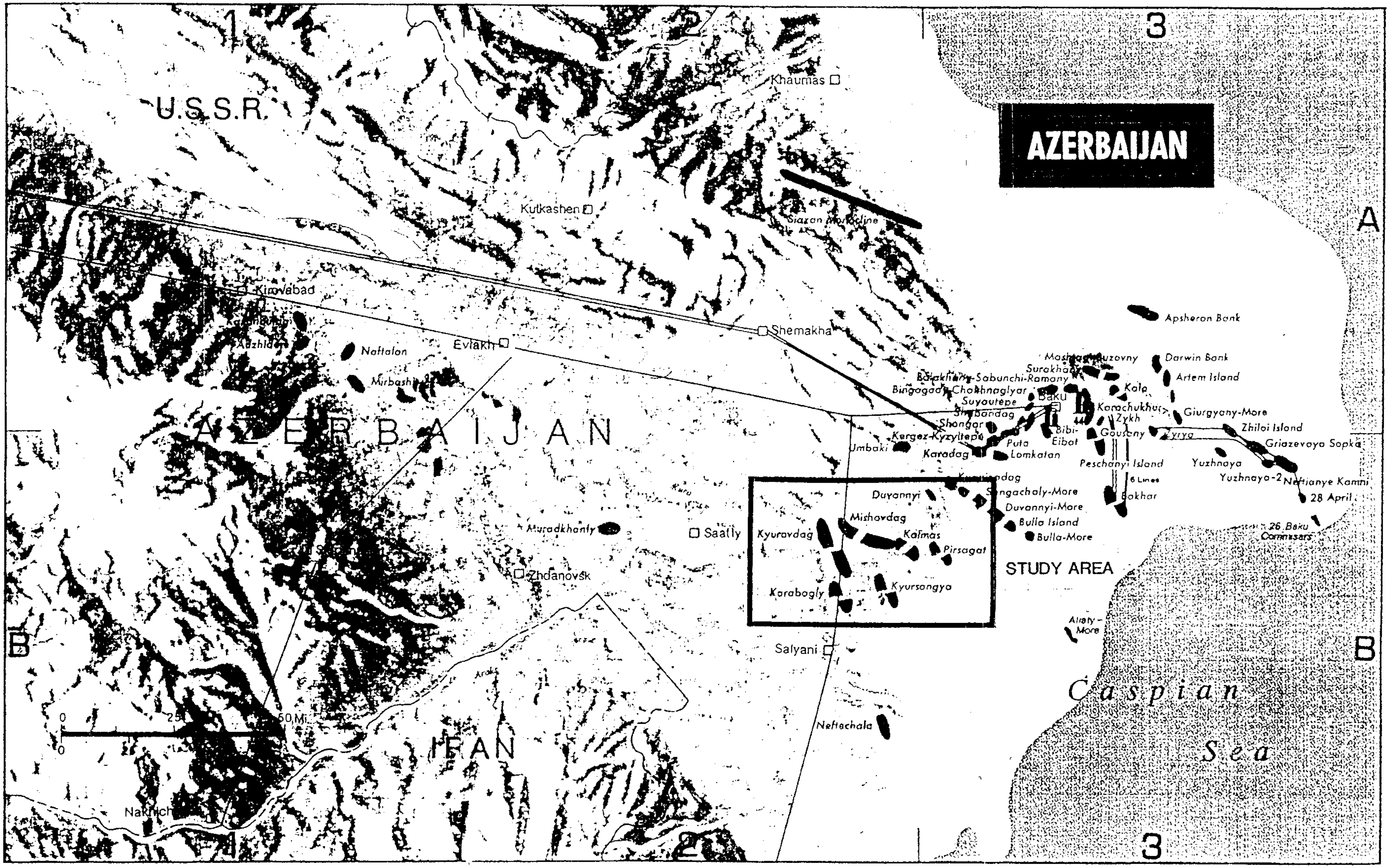
NO.	Equation	r	θ
1	$\ln\phi = 4.74 - 0.67\ln F$	0.83	1.79
2	$\ln\phi = 4.95 - 0.98\ln F_z$	0.47	1.13
3	$\ln\phi = 2.13 + 0.07E_{SP} - 0.001\,(E_{SP})^2$	0.65	1.31
4	$\phi = 13.6 + 0.62E_{SP} - 0.007(E_{SP})^2$	0.60	1.25
5	$\ln\phi = 2.81 + 0.83\,\alpha_{SP} - 0.37(\alpha)^2$	0.45	1.18
6	$\ln\phi = 2.52 + 0.09J - 0.003(J) + 0.0004(J)^3$	0.45	1.18
7	$\phi = 15.5 + 0.62J - 0.01(J)^2$	0.41	1.10
8	$\ln\phi = 2.91 + 0.34\ln(R_t/R_{mf}) - 0.11\,[\ln(R_t/R_{mf})]^2$	0.59	1.24
9	$\ln\phi = -4.19 + 13.4J - 8.1(J_n)^2 + 1.04(J_n)^3$	0.40	1.09
10	$\ln k = 3.26 + 2.29\alpha_{SP}$	0.37	1.09
11	$\ln k = 14.3 - 16.8\ln(E_{SP}) + 7.4(\ln E_{SP})^2 - 0.95(\ln E_{SP})^3$	0.44	1.11
12	$\ln k = 2.76 + 2.74\ln(R_t/R_{mf}) - 0.89[(\ln R_t/R_{mf})]^2$	0.44	1.11
13	$\ln k = 3.27 + 0.86J - 10^{-3}\,0.99(J)^2$	0.36	1.07
14	$\ln k = -4.37 + 10.4J_n - 2.9(J_n)^2$	0.36	1.07
15	$q = 0.69 - 0.024E_{SP}$	0.80	1.67
16	$C = 34.2 - 25.8\alpha_{SP}$	0.78	1.60
17	$C = 24.3 - 0.2J$	0.61	1.22
18	$C = 28.9 - 7.63J_n$	0.32	1.06
19	$q = 0.56 - 0.007J$	0.57	1.22

TABLE 4: MULTIDIMENSIONAL PETROPHYSICAL CORRELATIONS

NO.	Equation	r	θ
1	$\ln\phi = 2.61 - 0.11\ln F_z + 0.26\ln E_{SP}$	0.65	1.31
2	$\ln\phi = 5.59 + 0.30\ln E_{SP} - 0.09\ln F_z - 0.41\ln D$	0.75	1.51
3	$\ln\phi = 5.39 + 0.3\ln E_{SP} - 0.02\ln(R_i/R_{mf}) - 0.39\ln D$	0.80	1.67
4	$\ln\phi = 5.83 + 0.27\ln E_{SP} + 0.002J + 0.08J_n - 0.48\ln D$	0.75	1.51
5	$\ln\phi = 5.87 + 0.28E_{SP} - 0.09\ln F_z + 0.002J - 0.44\ln D$	0.75	1.51
6	$\ln\phi = 5.75 + 0.29E_{SP} - 0.16\ln R_i/R_{mf} + 0.002J - 0.42\ln D$	0.80	1.67
7	$\ln\phi = 5.94 + 0.45\alpha_{SP} - 0.18\ln T_f + 1.9\ln d_k$	0.53	1.18
8	$\ln k = 12.58 + 0.1E_{SF} - 0.53\ln(R_i/R_{mf}) - 1.16\ln D$	0.58	1.23
9	$\ln k = 15.84 + 0.08E_{SP} + 0.013J + 1.02J_n - 1.9\ln D$	0.65	1.31
10	$q = 0.71 - 0.013E_{SP} - 0.002J$	0.80	1.67
11	$q = 0.56 - 0.013E_{SP} - 0.003J + 0.9 \times 10^{-4}D$	0.84	1.84

U.S.S.R.

Figure 1: Location Map of the Studied Area.



fields discovered as long as 19 years ago in shallow Sea of Okhotsk waters near Sakhalin Island's northeast coast.

with foreign trade, covers proprietary geophysical and geological information for all the onshore areas of the Soviet

Figure 2: Statistical distribution of the gamma-ray shaliness factor.

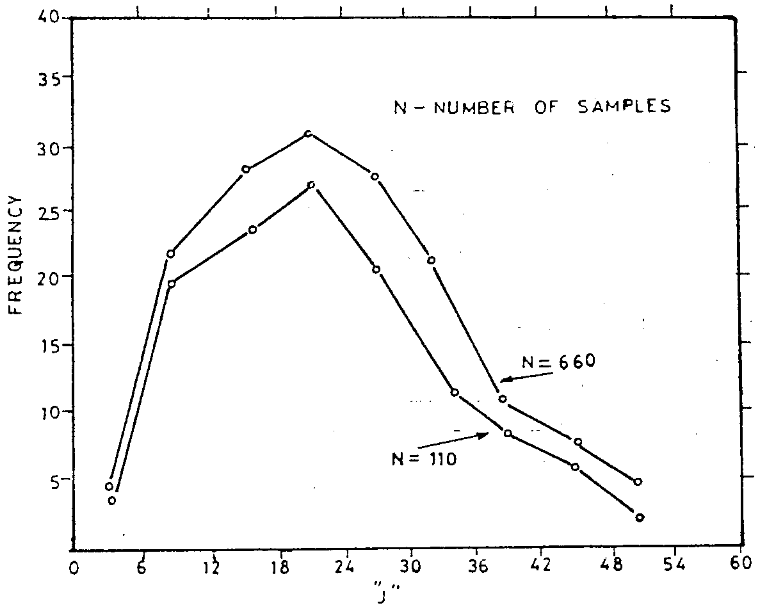


Figure 3: Statistical distribution of the clay content C.

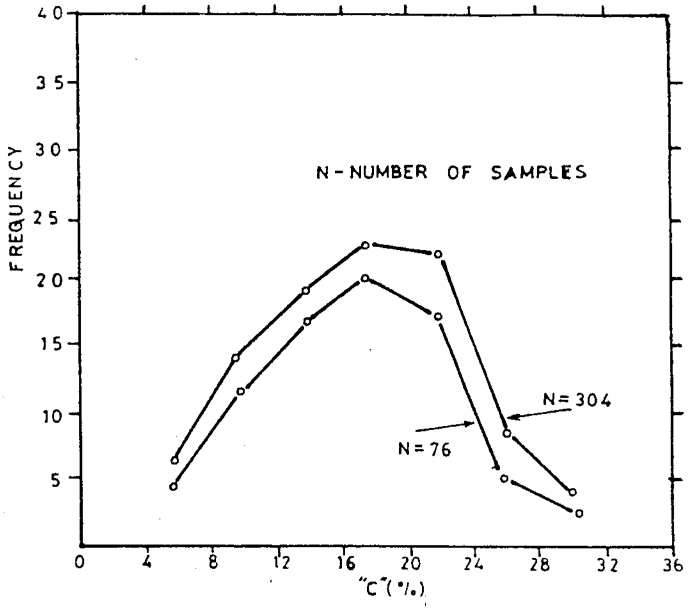


Figure 4: Flow chart of computer program for formation evaluation by multidimensional petrophysical correlations.

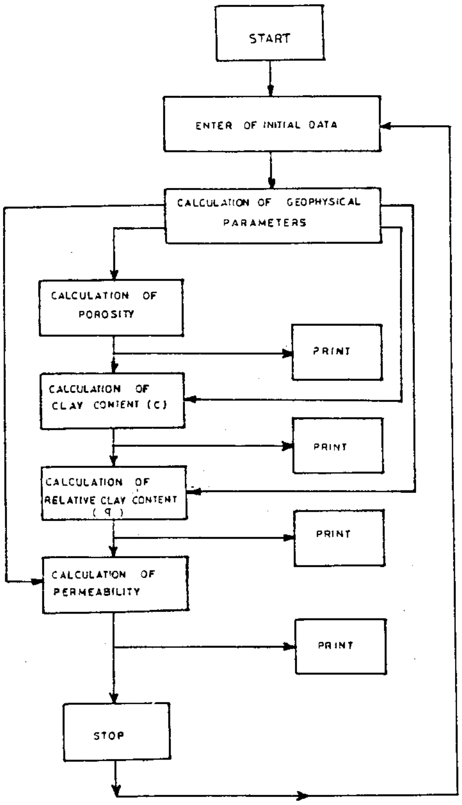


Figure 5: Kura River Region, Comparison of measured porosity (ϕ_m, %) with porosity values calculated by petrophysical correlation (ϕ_c, %).