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(72) Inventors ALBERTO KHATCHIKIAN, ANDRE POUPON and JEAN-CLAUDE FAVARD

(19)

(54) METHODS FOR PRODUCING SIGNALS REPRESENTATIVE OF PARAMETERS USED IN EVALUATING EARTH FORMATIONS

(71) We, SCHLUMBERGER LIMITED, a corporation organised and existing under the laws of the Netherlands Antilles, of 277 Park Avenue, New York, New York 10017, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed to be particularly described in and by the following statement:—

This invention relates to methods for deriving from well logging data signals representative of parameters used in evaluating earth formations.

In the field of oil prospecting, the determination of oil-bearing strata and the evaluation of hydrocarbons which can be moved and extracted can be made on the basis of data recorded in exploratory boreholes.

Methods allowing such evaluation by automatically combining signals representative of data obtained by well logging have been described in French Patents 71.02767 granted May 2, 1973 and published under No. 2,080,945 and 70.03544 granted March 13, 1972 and published under No. 2,102,380, both granted to Societe de Prospection Electrique Schlumberger.

The present invention is relative to an automatic combining process which may be preliminary to that described in the two preceding patents, which process is intended to produce signals representative of input parameters used to facilitate subsequent formation evaluation and to increase the accuracy and the reliability of the results.

The definitions of the terms used are explained in detail in the two earlier French patents.

Well logging consists of recording, as a function of depth, certain values furnished by measuring instruments moved along a borehole.

The recorded information usually includes the following:

1) the depth Z;
2) the diameter of the hole measured;
3) the apparent porosity ϕ_N of the formations measured by a neutron probe and expressed in porosity units p.u.;
4) the bulk density of a formation ρ_b.

If ρ_{ma} is used to designate the density of the matrix, i.e., of the formation assumed to be non-porous, and ρ_f the density of the fluids filling the pores, the measurement of ρ_b makes it possible to obtain an evaluation ϕ_D of the porosity by the formula:

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad (1)$$

5) The time Δt taken by an acoustic wave to cover a given distance, or sonic transit time;

This measurement furnishes a third estimation ϕ_S of the porosity by the formula:

$$\phi_S = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \qquad (2)$$

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in which Δt_{ma} and Δt_f are the times for travelling the same distance in the rock constituting the matrix and in the fluid contained in the pores.

6) The spontaneous potential SP expressed in millivolts;

7) The natural gamma radioactivity GR expressed in A.P.I. units;

8) The true resistivity R_t expressed in ohms.M²/m. This resistivity can be obtained either by measuring an induced current, R_{ILd} or by measuring a potential difference between two electrodes R_{LL}. It furnishes an estimation of a parameter ϕR_t representing the amount of water per unit volume of the formations, by the formula:

$$\phi R_t = \sqrt[n]{\frac{a \cdot R_w}{R_t}} \qquad (7)$$

in which n is an exponent taking on values generally between 1.8 and 2.2, and a is a constant coefficient generally between 0.6 and 1. In non-argillaceous water-bearing formations ϕR_t is equal to the porosity.

9) The resistivity of the zone invaded by the mud filtrate R_{xo} in ohms.m²/m. This is measured through the potential difference between two electrodes: R_{MLL}.

S_w designates the formation water content of the pores, also called the water saturation, i.e., the ratio of water volume to pore volume. Likewise, S_{hy} designates the liquid or gaseous hydrocarbon content of the pores.

$$S_w + S_{hy} = 1 \qquad (3)$$

that is, all the pores are filled with fluid: water, oil or gas.

In the zone near the borehole, which is invaded by the mud filtrate, S_{xo} designates the mud filtrate saturation and S_{hyr} the residual hydrocarbon saturation.

$$S_{xo} + S_{hyr} = 1 \qquad (4)$$

S_{hyr} represents the proportion of irretrievable hydrocarbons while the difference $S_{hy} - S_{hyr}$ represents the hydrocarbons which can be moved and extracted.

One of the results sought in the evaluation of a porous formation is the value of the product $\phi x\ (S_{hy} - S_{hyr})$ or $\phi x\ (S_{xo} - S_w)$ which represents, for each stratum, the proportion of the formation volume occupied by retrievable hydrocarbons.

The presence of hydrocarbons in a formation greatly modifies certain measured parameters, in particular the resistivity, because the resistivity of hydrocarbons is much higher than the resistivity R_w of the formation water.

However, the nature of the minerals constituting the matrix of the rock gives rise to very substantial variations in the measurements, in particular the presence of clay (Cl) in all its forms: colloidal clay or clay loam.

Potential reservoirs of hydrocarbons can be found in rock formations made up of one or more minerals such as limestone, dolomite or sandstones with no clay or with clay in various amounts, and in sands also with or without clay; the clay being usually associated with shale. It can be found convenient to distinguish between two basic models corresponding to the two different situations above for evaluating the formations: formations of unknown lithology with clay and shaly sand formations.

In the case where the lithology is not accurately known, variations due to the hydrocarbons and to lithological factors can occur in the same or opposite direction so that, to be able to determine with good accuracy which strata contain hydrocarbons and to be able to evaluate the retrievable volume of hydrocarbons, it would be desirable, using signals representative of well logging data obtained and combining them, to determine the lithology of the strata, and such input parameters as clay proportion, clay and formation water parameters, and parameters to calibrate some of the measurements, particularly those from the porosity measuring tools so that the values of porosity ϕ given by the different instruments are the same.

In shaly sands, although the minerals of the formation are essentially known, the amounts of silt and wet clay associated with shale are not generally known. It would thus be desirable by automatically combining signals representative of well logging data to determine such input parameters as the neutron and density derived porosity for wet clay, maximum resistivity of shales, neutron derived porosity for hard shales, maximum porosity of the formation and others as well as calibration parameters to correct such measurements of hydrogen content and bulk density.

In the two earlier French patents, a description was given of methods for the automatic combining of signals representative of well logging measurements which required such input parameters as a preliminary step to detailed evaluation of the formation at successive depth levels.

It is the general object of the present invention to provide methods for producing signals representative of input parameters used in evaluating earth formations by automatically combining signals which are derived from well logging measurements of various earth formation characteristics.

According to one aspect of the invention, there is provided a method for automatically determining a correction factor useful for evaluating earth formations traversed by a borehole, comprising:

deriving measurements of a plurality of subsurface characteristics at different depth levels in a section of the borehole;

using at least some of said measurements to automatically select a set of less argillaceous depth levels in the borehole section;

producing a function of first and second parameters derived from measurements of first and second subsurface characteristics at said selected depth levels;

modifying at least the first parameter at said selected depth levels by a first variable correction factor; and,

determining a value of said first correction factor which optimizes said function to correct said first parameter.

According to another aspect of the invention, there is provided a method of automatically determining a calibration correction useful for evaluating earth formations traversed by a borehole, comprising:

deriving measurements of a plurality of subsurface characteristics at different depth levels in a section of the borehole;

using at least some of said measurements to automatically select in the borehole section depth levels correspoding to low porosity formations;

detecting a lithological structure at some of said selected depth levels on the basis of parameters derived from said measurements at said selected depth levels; and

determining, on the basis of a known value of a selected characteristic of the formations in the detected lithological structure, a calibration correction to be applied to measurements of said selected characteristics.

A first description is given below of the various stages of a particular procedure for a situation where the formation lithology is not well known. While this particular method could be carried out on an analog signal combining device, it is preferred that it be carried out on an appropriately programmed general purpose digital computer.

A second description is then given of the application of principles of the invention to a shaly sand type of formation.

The invention will now be described, by way of example only, with reference to the appended drawings, of which:

Fig. 1 represents a graphic combination of the measurements of ϕ_N and ϕ_D for various minerals commonly found in earth formations;

Figs. 2 to 10 represent flow charts depicting successive signal determinations and combinations for carrying out one aspect of the invention according to the first description;

Fig. 11 illustrates an exploring apparatus for deriving well logging measurements and associated apparatus for recording and processing the measurements.

Figs. 12, 13 and 14 are crossplots of certain measurements useful in describing features of the present invention in accordance with the second description.

Figs. 15 to 26 represent flow charts depicting successive signal determinations and combinations for carrying out another aspect of the invention according to the second description.

Referring to Fig. 11, there is shown an investigating apparatus 420 located in a borehole 421 on the end of a multi-conductor cable 422 which is raised and lowered in a borehole by a suitable drum and winch mechanism (not shown). Investigating apparatus 420 includes exploring devices for: obtaining measurements of the acoustic travel time, Δt; bulk density ρ_b; the porosity ϕ_N derived from a neutron exploring device; the natural gamma ray count, GR, of a formation; the diameter of a borehole, caliper; the spontaneous potential, SP; deep and shallow resistivities, R_t and R_{xo}.

An acoustic exploring device for deriving a measure of Δt can be found in U.S. Patent No. 3,231,041 granted to F. P. Kokesh on January 25, 1966. An example of an exploring device for obtaining a measure for the neutron derived porosity ϕ_N can be found in U.S. Patent No. 2,769,918 granted to C. W. Tittle on November 6, 1956. An exploring device for obtaining a measure of the bulk density can be found in U.S. Patent No. 3,321,625 granted on May 23, 1967 to John S. Wahl. An exploring device for obtaining measurements of the spontaneous potential and deep and shallow

resistivity can be found in U.S. Patent No. 3,453,530 granted to G. Attali on July 1, 1969.

Measurement signals derived from the exploring device 420 are transmitted to a suitable processing circuit 425 at the surface of the earth. Signal processing circuits 425 prepare the signals for application to a digital tape recorder 426 which converts the well logging signals to digital form for recording on magnetic tape. The resulting magnetic tape is either carried to digital computer 427 or the data transmitted via a telemetry link to the digital computer which is programmed to process the data in a manner to provide valuable information relative to the nature of the earth formation. While all the measurements to be used in practicing the present invention have, in Fig. 11, been shown derived from one exploring device it is to be understood that these measurements can be derived from a plurality of exploring devices which are run through the borehole at different times. In this event, the data from each run would be recorded on individual magnetic tapes and the data on each tape would be merged into a single tape for use by digital computer 427.

Referring now to Fig. 1 there is shown a diagram in which the abscissas are the measured values of the neutron porosity ϕ_N and the ordinates are the values of the porosity ϕ_D computed from the density ρ_b, the measuring instruments being calibrated in limestone.

In this graph are represented the curves corresponding to the three most frequent matrices: dolomite (Dol), limestone (C) and sandstone (Gr).

Each level is represented on the graph by a point whose abscissa is the measured value of ϕ_N and whose ordinate is the measured value of ρ_b. All the levels of an interval furnish a cluster of points.

The points corresponding to the limestone levels are grouped along the line (C) for which $\phi_N=\phi_D$ since the measuring instruments are calibrated in the limestone.

The points corresponding to the sandstone levels are grouped along the curve (Gr) and the points corresponding to the dolomite levels are grouped along the curve (Dol). The curves (C), (Gr) and (Dol) are graduated in porosity units.

For a given borehole, the nature of the traversed formations is known as well as the two end matrices, for example, limestone and dolomite if carbonate formations are involved. The apparent densities ρ_{ma1} and ρ_{ma2} of these matrices are read on the diagram at the end of the curves in the neighborhood of $\phi_N=0$ and the porosities $\phi_{N\,ma1}$ and $\phi_{N\,ma2}$ which correspond to the abscissa of the end of the curves.

Any level is generally a mixture of several matrices with clay and occasionally hydrocarbons and the point which represents it can fall outside of the curves representing the simple matrices. The porosity ϕ_{ND} of this level is obtained graphically by plotting one of the lines parallel to the constant porosity lines passing through this point. For example, the level A which $\phi_N=20$ and $\rho_b=2.45$ has a porosity $\phi_{ND}=18.5$.

The calibrations of ϕ_N and ϕ_D result in shifting the cluster of points representative of all the measurements.

If the only variable factor were the lithological nature of the matrix, all the points of the cluster should be situated between the two curves representing the end matrices.

The method hereinafter described includes, first, marking the low-clay and water-bearing strata and, then, calibrating the measurement tools for porosity ϕ_N and for density ρ_b so that the maximum of these points, after the shifts due to calibration, are located between those of the two curves (Dol), (C) and (Gr) which correspond to the end matrices present in the borehole.

The point B represents the mud filtrate which in general corresponds to $\rho_b=1$ and $\phi_N=100\%$.

The points representative of the clay levels are grouped along a line BB called the clay line. The density corresponding to the point D where the clay line intersects the axis $\phi_N=0$ is the apparent matrix density of the clay $\rho_{ma\,Cl}$, close to 3 in the figure.

The point B represents a pure clay level having a density $\rho=2.45$ and a neutron porosity $\phi_N=0.27$.

The point F, determined by the intersection of the line EM with the $\phi_N=0$ axis, represents the apparent matrix density of a point M having $\phi_N=.20$ and $\rho_b=2.55$.

With the point M representative of a level, i, located in an interval in which the matrix of the rocks is composed of limestone, we obtain the clay proportion $V_{Cl(i)}$ in this level through the ratio FI/DI in which I is the point where the line C intersects the axis $\phi_N=0$.

Fig. 2 represents the flow chart of the overall operation. This includes four stages:

Stage I: input of information.

Stage II: calibrations in low porosity formations.

Stage III: determination of argillaceous strata and clay parameters.
Stage IV: calibration in water-bearing formations.

Stage I—Input of Information

Fig. 3 represents the general flow chart of Stage I: input of information.

A first item of information is the minimum and maximum depth between which falls the borehole length to be studied, in the case where the study must include only one portion of the borehole (block 1).

Block 2 represents the reading of the measurements made in the borehole. These readings have been previously corrected to take into account the diameter of the borehole and the possible presence of a mudcake along the walls.

These corrections are made from nomograms which indicate the variations in the readings brought about by variations in diameter. The measurements made are those which correspond to regularly spaced depth levels for example, every 30 centimeters or every foot.

Block 3 represents the values of the constant parameters which are recorded for each geological stage. The geological stages are determined by a preliminary analysis of the borehole data.

These parameters are:

Z1 and Z2: limit depths of each geological stage previously marked.

T: temperature at different levels.

R_{mf}: known mud filtrate resistivity. This resistivity varies with temperature according to the formula:

$$R_{mf}=R_{mfo}\frac{82}{TF+7} \qquad (8)$$

in which R_{mfo} is the resistivity at 75°F and TF the temperature in degrees Fahrenheit.

R_w: resistivity of formation water if known. This resistivity also varies with temperature according to the formula (8).

If R_w is not known with accuracy, we enter an approximated value, R_{wa}.

ρ_{ma1} and ρ_{ma2} which are the maximum and minimum matrix densities present in the borehole.

The lithology of the traversed formations is sufficiently known so that these densities can be determined. In general, the minerals present, in addition to clay, are sandstone, whose matrix density is about 2.65, or limestone with a density $\rho_{ma}=2.71$ or dolomite with a density $\rho_{ma}=2.87$.

For the sands, the matrix density ρ_{ma} can vary according to their composition: the average density of the sands is entered if it is known.

$\phi_{N\,ma\,max}$ and $\phi_{N\,ma\,min}$ are the matrix porosities read on the neutron probe for the end matrices corresponding to ρ_{ma1} and ρ_{ma2}. These values are also known. For limestone, $\phi_{N\,ma}=0$ because the neutron probe is calibrated for limestone.

For dolomite, $\phi_{N\,ma}=0.5$ p.u.

For quartz sand, $\phi_{N\,ma}=-3$ p.u.

ρ_h: density of hydrocarbons. If the type of hydrocarbons present is known, this information can be given. Otherwise, we take $\rho_h=0.7$ for the oil, but the actual values can be much lower in the case of gas.

We also indicate, if they are known, the levels at which are located the major geological contacts between two geological stages of a different nature.

Loop 3a indicates that the values of the constant parameters are recorded for each geological stage for the entire borehole length. After the parameters have been recorded, the information reading stage is ended and the program proceeds to Stage II.

Stage II—Calibrations in the low porosity formations

The purpose of this stage is to find the low porosity levels of anhydrite, salt or compact rocks if these exist and to use the readings in these levels to calibrate the porosity measuring instruments.

This stage is divided into two phases:

Phase II_1: phase for determining the low porosity levels.

Phase II_2: correction of measurements from readings corresponding to the low porosity formations.

Phase II_1:

Fig. 4 represents the flow chart of the phase II.

Block 4 represents three indices NxS, NxAN and NxPD which designate the number of levels of salt, anhydrite and of compact formations respectively which have been noted. At the beginning of Stage II, these three indices are set to zero. The stored information is read, block 4a. Then for each item of information, we first determine whether the depth level is in the geological stage, i.e., whether the depth Z is between Z_{max} and Z_{min} (block 5). If the depth level is outside the geological stage, it is first asked if all the data has been used, and if it has not, the information from the next geological stage is read and the depth level is processed using the information from the proper geological interval.

If the depth level is within the geological stage, doubtful information is eliminated by cutting out all readings which correspond to levels in which the diameter exceeds a certain limit or to levels in which the parameter $\Delta\rho_b$, which is recorded at the same time as the density ρ_b shows a measurement which is likely to have an error (block 6).

Next, ϕR_t is computed using Eq. 7 (block 6a). We determine whether ϕR_t is lower than 5 porosity units. If such is not the case, we go on to the next level. If such is the case, we determine whether $\phi R_t \leq 1$ (block 8). In the affirmative, the corresponding level can be salt or anhydrite.

We determine whether it is salt by successively checking whether the measured density ρ_b is between 2 and 2.1 (block 9), whether the measured radioactivity $GR \leq 20$ (block 10) and whether the acoustic travel time $65 \leq \Delta t \leq 69$ (block 11). If these conditions are all met, it can be concluded that a salt level is involved. In this case, we increase the index NxS by one unit and store the density and the porosity measured for this level, which correspond to the parameters of the salt: ρ_b salt and ϕ_N salt (block 12). If the density ρ_b is not between 2 and 2.1, NO answer from decision element 9, we determine whether an anhydrite stratum is involved, i.e., whether simultaneously $\rho_b \geq 2.9$ (block 13), $GR \leq 20$ (block 14) and $48 \leq \Delta t \leq 52$ (block 15). If the answer to these three questions is affirmative, it is concluded that an anhydrite level is involved.

The index NxAN is increased by one unit and the corresponding measurements $\rho_b A_N$, ϕ_{NAN}, Δt_{AN} and ϕR_{tAN} which represent a measurement in the anhydrite (block 16) are stored.

If the block 8 has determined that ϕR_t, while being lower than 5, was higher than 1, we determine whether the level is a compact formation such as limestone or dolomite. Such formations exhibit a high resistivity, higher than 1000 times R_w and a total density $\rho_b \geq 2.60$.

Blocks 17 and 18 determine whether these two conditions are verified simultaneously.

If the number of levels available is relatively limited we conserve all the levels for which the porosity measured by the neutron probe $\phi_N \leq 5$ p.u.

If, on the other hand, many measurements are available, corresponding to compact formations, we make a more severe selection and retain only the levels for which the porosity ϕ_N is less than or equal to $(\phi_{N\,min}+3)$, $\phi_{N\,min}$ being the lowest of the porosity values measured, which can be negative (block 19).

An index NxPD is increased by one unit if all the conditions are met (block 10). The measured value of ϕ_N, ρ_D and Δt are also recorded.

Phase II_1 is pursued until all the data are used and then the program proceeds to Phase II_2.

Phase II_2:

Fig. 5 represents the flow chart of this phase which is designed to calibrate the porosity and density reading instruments from the information obtained in the low porosity levels which have been marked and recorded during the phase II_1.

Block 21 determines whether the number of anhydrite levels is sufficient to lead to statistically valid results, for example greater than 20.

If such is the case, a first correction of the measurement instruments is carried out.

We determine the statistical maximum $\rho_{b\,max}$ of all the values of ρ_b measured in the anhydrite levels and we make a scale shift $d\rho_b$ of the measurements of ρ_b so that $\rho_{b\,max}=2.98$ which is the correct reading of the anhydrite.

Likewise, we calculate the statistical minimum $\phi_{N\,min}$ of all the porosity measurements made with the neutron probe for all the anhydrite levels and we adopt a calibration $d\phi_N$ of ϕ_N such that $\phi_{N\,min}=-0.005$.

We also calibrate the instrument measuring the acoustic travel time Δt so that

the statistical minimum Δt_{min} of all the values measured in the anhydrite strata becomes equal to 50 after a scale shift d Δt.

If the borehole has gone through a thick zone of anhydrite, for example at least 3 meters thick, i.e., having at least 10 successive measurements noted as corresponding to anhydrite, we note the value of the conductivity, CIL, measured by the induction probe or the average of the conductivity values and, if the difference between the diameter of the borehole and the diameter of the drill bit is smaller than 2 inches, we make an origin shift d CIL such that CIL+d CIL=0.

All these operations are represented in the flow chart by block 22.

A general technique for finding the statistical maximum of a parameter is to find or compute the maximum of the function:

$$P(i)=\sum \frac{sign(i,j)}{1+\alpha\,|x_i-x_j|^n}$$

where α is a positive coefficient and n is a positive exponent, for example 2. The subroutine for performing this operation is shown in Fig. 5a.

Referring to Fig. 5a, the subroutine is entered, block 250 and the parameters MAX, Σ_j and P_i are initially set to 0, block 251. MAX represents the maximum computed value of the function P_i and Σ_j is the running sum of the function P_i.

The first depth level is considered by setting i and j equal to 1, block 252 and 254. Then, the difference in the value of the parameters at depth levels i and j which are indicated by x_i and x_j respectively, is computed, block 256 after which decision element 258 asks if this difference is equal or greater than 0. If it is, sign (i, j) is set equal to +1, block 260 and if not, sign (i, j) is set equal to −1, block 262. The function

$$\frac{\text{sign (i, j)}}{1+\alpha|x_i-x_j|^n}$$

can now be computed for the levels corresponding to i and j and added to Σ'_j which is the sum of the functions computed for the previous j levels. This is indicated in block 264. Next, decision element 266 asks if j=N, i.e., if all the levels j have been considered, and if not, j is incremented block 268 while i remains constant for the next computation. After all N levels have been considered by incrementing j and maintaining i constant, P_i is set equal to the sum of the function computed in block 264, as represented by block 268. Next decision element 270 asks if P_i is greater than MAX and if it is, MAX is set equal to P_i, block 272. Decision element 274 next asks if *i* equals N, that is if i has been varied over all N depth levels of interest. If not, i is incremented, block 272 and the program returns to consider the next i depth level with all j depth levels. This continues until all the depth levels have been considered after which the maximum value P_i equal to MAX for the entire computation is taken as the statistical maximum value of the parameter of interest, block 278 and the program returns, block 280.

To compute the statistical minimum of a parameter, the same procedure is followed except that the value sign (i, j) is taken as opposite that of the difference (x_i-x_j). Thus in flow chart of Fig. 5a, after decision element 258, sign (i, j) would be set equal to +1 if (x_i-x_j) is less than zero and sign (i, j) would be set equal minus one if (x_i-x_j) is equal to or greater than zero.

Block 23 indicates that the value 1 is given to an index IT_{AN} indicating that a calibration was made in the anhydrite.

If the response of the block 21 is negative, the total thickness of anhydrite is insufficient for a valid calibration, and the block 24 determines whether the number of compact levels detected NxPD is sufficient, for example higher than 20.

If affirmative, block 25 indicates the calculations carried out.

We calculate the average value of all the porosity measurements ϕ_N obtained by the neutron probe in the compact formations. We also calculate, for each compact formation, a porosity value ϕR_t from the resistivity measurement, R_t and an approximate value of R_w by the formula (7) with, for example, n=2.15 and a=0.62 and we determine the average of all these values ϕR_t. For each compact stratum, we calculate the matrix density ρ_{ma} R_t from the total density measurement ρ_b and from the calculated value of ϕR_t by the formula:

$$\rho_{ma}\,R_t=\frac{\rho_b-\phi R_t.\rho_f}{1-\phi R_t} \qquad (9)$$

which formula is derived from the formula (1) by replacing ϕ_D by ϕR_t.

We then determine the statistical maximum $\rho_{ma}R_{t\,max}$ and and statistical minimum $\rho_{ma}R_{t\,min}$ of all these values of $\rho_{ma}R_t$ and we calculate the range of variations $D\,\rho_{ma}R_t=\rho_{ma}R_{t\,max}-\rho_{ma}R_{t\,min}$.

Block 26 indicates that an index $IT_{PD}=1$ is recorded indicating that a calibration is made in the compact levels.

Block 27 indicates that a calibration $d\,\phi_N$ is made on the neutron probe.

The scale shift $d\,\phi_N$ is taken equal to the difference between the average value of ϕR_t and the average value of ϕ_N in the compact formations so that the average of the measurements of ϕ_N after correction becomes equal to the average of the values of ϕR_t.

Before calibrating the density measuring instrument, block 28 determines whether the variation range $D\,\rho_{ma}R_t$ is between 0.15 and 0.17. These limits correspond to the difference between the matrix densities of the dolomite and of the limestone which is 0.16.

If the response of block 28 is affirmative, we deduce that compact formations contain levels of limestone and levels of dolomite in the pure state.

Block 28a indicates that we then carry out the calibration of the measuring instrument for the density ρ_b by shifting the scale by a quantity $d\rho_b$ such that $\rho_{ma}R_{t\,max}$ is equal to 2.87, i.e., to the density of the dolomite. Simultaneously, $\rho_{ma}R_{t\,min}$ becomes equal to 2.71 since $D\,\rho_{ma}R_t$ is essentially equal to 0.16.

If the response of block 28 is negative, block 29 determines whether $D\,\rho_{ma}R_t$ is small, for example smaller than 0.05.

If the response is affirmative, the compact formations are composed of a single mineral: limestone or dolomite.

To determine the nature of this mineral, it is necessary to measure the acoustic travel time Δt from which we determine the acoustic travel time in the matrix Δt_{ma} by the formula:

$$\Delta t_{ma}=\frac{\Delta t-\phi_{No}.\Delta t_f}{1-\phi_{No}} \qquad (10)$$

in which formula Δt_f is the known acoustic travel time in the fluid which fills the pores and ϕ_{No} indicates the corrected value of the porosity measurement by the neutron probe.

Block 30 indicates the calculation of the average value of all the values of Δt_{ma} in the compact formations.

Block 31 determines whether the average Δt_{ma} is smaller than 44. If it is, the compaction formations are dolomite.

Block 32 indicates that the density measuring instrument must be calibrated using a correction $d\,\rho_b$ such that $\rho_{ma}R_{t\,max}=2.87$.

If the response of block 31 is negative, block 33 determines whether the average value of Δt_{ma} is between 47 and 49. If it is, the compact formations are limestone strata. Block 34 indicates that the density measuring instrument must be calibrated using a correction $d\,\rho_b$ such that $\rho_{ma}R_{t\,min}=2.71$.

Coming back to block 29, a negative response means that the compact formations are composed of mixtures of limestone and dolomite.

The function of block 35 is to determine whether the limestone or the dolomite are predominant in this mixture. To accomplish this, the respective weights of the statistical maximum and minimum of $\rho_{ma}R_t$ are compared.

If the limestone is predominant, the histogram of the values of $\rho_{ma}R_t$ exhibit an accumulation in the neighborhood of the statistical minimum whereas this accumulation is located in the vicinity of the statistical maximum if the dolomite is predominant.

To differentiate these two cases, we assign to the statistical minimum and maximum a weight function:

$$P=\sum_{xil-0.03}^{xil+0.03} R_{(xi)} \qquad (11)$$

in which xil is the statistical minimum or maximum of all the values of $\rho_{ma}R_t$ and R is the ordinate of the histogram, i.e., the frequency of the values. The function P thus corresponds to the integration of the histogram over an interval 0.03 wide on either side of the statistical minimum and maximum.

If block 35 determines that the weight of $\rho_{ma}R_{t\,max}$ is lower than that of $\rho_{ma}R_{t\,min}$ the matrix of the compact formations is composed mainly of limestone and the measurement of ρ_b is calibrated in the limestone (block 34).

If, on the other hand, the weight of $\rho_{ma}R_{t\,max}$ is higher than that of $\rho_{ma}R_{t\,min}$ then the matrix of the compact formations is composed mainly of dolomite and the measurement of ρ_b is calibrated in the dolomite (block 32).

Before recording the correction $d\rho_b$ of the density measurement determined by block 32 or block 34, the block 36 determines whether this correction is smaller than 0.05. If it is, the correction is recorded (block 37).

By contrast, if $d\ \rho_b > 0.05$, it is concluded that the value is too high and that an error is to be feared.

In this case, the calibration in the compact formations is rejected (block 38) and the operations are pursued working with the salt levels.

If the response of block 24 is negative, or after having carried out the calibrations in the anhydrite levels and/or in the compact formations, block 39 determines whether the number of salt levels is sufficient. If the reply is affirmative, a correction $d\ \rho_b$ is made in the density measuring instrument so that the statistical minimum ρ_b obtained in the salt is equal to the correct reading for the salt, or 2.03. The index ITS is given the value 1 to indicate that a correction has been made in the salt (block 40).

In the case where the borehole traverses both anhydride and salt, we thus obtain a double calibration of the measurements of ρ_b at the two ends of the scale. If these two calibrations are identical, it is then sufficient to make a scale shift. On the other hand, if they do not correspond, it is necessary to introduce at the same time a multiplying coefficient C or a sensitivity coefficient for the measurements of ρ_b so that they correspond and, in this case, the calibration of the density measuring instrument is finished.

Block 41 determines if there has already been a calibration in the anhydrite, in which case we go on to Stage III.

Block 42 also determines whether a calibration has been made in the compact formations, in which case we go on to the next stage.

On the other hand, if no calibration has been made in the anhydrite, nor in the compact formations, we determine the statistical minimum $\phi_{N\,min}$ of all the values of ϕ_N measured by the neutron probe in the salt levels and we make a correction $d\ \phi_N$ such that $\phi_{N\,min}=0.035$ (block 43).

Stage II is then finished.

Summarizing, during this stage, we have calibrated the measuring instruments for porosity, density and possibly for acoustic travel time by shifting the zero of the scale.

If both anhydrite and salt exist in a sufficient thickness, the density calibration is completed and the only possible unknown calibration remaining is a scale multiplying factor of the porosity measurements by the neutron probe.

Stage III—Determining clay levels and clay parameters

Clays do not have specific properties which can be measured by logging making it difficult to detect the very argillaceous levels and to obtain the clay parameters.

To identify the clay levels, it is necessary to use the simultaneous variations of several clay indicators.

Thanks to the calculation of an optimizing function in which all these indicators are taken into account, it is possible to determine which levels are the most argillaceous and which are very probably composed of pure clay, and to derive a value of the clay parameters utilizable in the rest of the operations.

The measurements made in the borehole contain certain parameters and make it possible to calculate other parameters which vary as a function of the presence of clay and which are generally maximum or minimum in pure clay. Clay indicators are selected from among these variable parameters.

The variable parameters taken into consideration are the following:

a) the natural measured gamma radioactivity GR which, in general, is maximum in the clay;

b) the measured spontaneous potential which is maximum or minimum in the clay depending on the polarity;

c) the calculated product $GR \times \phi_N$ in which ϕ_N is the porosity measured by the neutron probe.

To avoid the causes of error which could be due to radioactive formations, all measurements of GR higher than 150 are eliminated.

The product $GR.\phi_N$ is maximum in the clay.

d) the apparent matrix density ρ_{maa} calculated according to the formula:

$$\rho_{maa} = \frac{\rho_b - \phi_N . \rho_{mf}}{1 - \phi_N} \qquad (12)$$

in which ρ_b and ϕ_N are the density and the neutron porosity measured and ρ_{mf} is the density of the filtrate present in the pores, which is known. The density ρ_{maa} is maximum in the clay. To avoid errors due to other formations having a high matrix density, the low porosity levels are eliminated by making a cut on the small values of ϕ_N. The anhydrite strata have been noted during the Phase II and are already eliminated.

e) The ratio ϕ_D/ϕ_N which is minimum in the clay. Since the calculation of ϕ_D requires that we know the matrix density ρ_{ma} which generally is not known, the following equivalent parameter is calculated:

$$N' = \frac{A - \rho_b}{\phi_N + B} \qquad (13)$$

(where A and B are constants typically set at 3.05 and 0.20 respectively) which parameter is also minimum in the clay.

f) the calculated ratio:

$$M = \frac{\Delta t_f - \Delta t}{100\,(\rho_b - \rho_{mf})} \qquad (14)$$

in which expression Δt is the measurement of the acoustic travel time in the formation, Δt_f the acoustic travel time in the fluid which fills the pores and ρ_{mf} the density of the mud filtrates.

This ratio is minimum in the clay.

g) the calculated ratio:

$$M' = \frac{100\,(C - \rho_b)}{\Delta t - D} \qquad (15)$$

(where C and D are constants, typically 3.05 and 20 respectively) which ratio is minimum in the clay.

h) the measured diameter of the borehole d, maximum in the clay.

The Stage III includes several phases.

—Phase III_1—for selecting the best clay indicators.

—Phase III_2—for determining the most argillaceous level or best clay zone and the least argillaceous level or best clean zone of each interval.

—Phase III_3—for determining the clay parameters.

Phase III_1:

The purpose of Phase III_1 is to select, from among the eight variable parameters sensitive to the presence of clay, the best clay indicators of which there are at least two. In the chosen example, the number of clay indicators is taken equal to at least five to improve accuracy.

This selection is obtained by calculating mutual correlation coefficients of the parameters and by retaining those which have the best correlation between them.

If we consider two variable parameters x and y, whose values corresponding to a level i are x_i and y_i, the correlation coefficient Cxy between these two parameters is calculated by the known formula:

$$Cxy = \frac{\sum_{i=1}^{n} x_i \cdot y_i - n\,\bar{x}\cdot\bar{y}}{\sqrt{\sum_i (x_i-\bar{x})^2 \cdot \sum_i (y_i-\bar{y})^2}} \qquad (16)$$

in which $\bar{x}$ and $\bar{y}$ are the average values.

It is known that the correlation is perfect if Cxy is close to 1, poor if $|C|<0.5$, good if $C>0.5$ and that there is an anti-correlation if $C<-0.5$.

In the example shown, we calculate for each geological stage the mutual correlation coefficient between each pair of variable parameters sensitive to clay. It would also be possible to calculate the correlation coefficients by intervals within each stage. We construct a square matrix of which each line and each column corresponds to one of the variable parameters and we place in the box corresponding to each intersection the mutual correlation coefficient between the two parameters corresponding to the line and to the column.

We take the sum of the absolute values of each line. The pivot indicator is the one having the maximum sum. We consider the two parameters corresponding to the two highest sums of absolute values. We keep as the best clay indicators the parameters which have a correlation coefficient with the two best parameters higher than 0.6 in absolute value. If the number of indicators thus selected is not equal to at least five, we retain the best five indicators having the best correlation coefficients with the two selected parameters.

We determine at the same time the polarity of S.P. from the sign of the coefficient of correlation between S.P. and the pivot indicator.

The pivot indicator is assigned a positive sign if it is maximum in the clay and a negative sign in the opposite case. The polarity of the spontaneous potential in the clays has the same sign as the product of the sign of the pivot indicator multiplied by the mutual correlation coefficient between S.P. and the said pivot indicator.

To say that S.P. has a positive polarity means that its value in the clays is higher than in the clean formations and that it has a maximum value in the clays, and vice versa if the polarity is negative.

Phase III_2:

Each geological unit is divided into intervals of a given height, for example intervals of 250 feet or 75 meters.

The purpose of phase III_2 is to determine, in each interval, the most argillaceous level or best clay zone and the least argillaceous level or best clean zone.

It is considered that these levels are those which optimize a choice function in the calculation of which are included the values of the selected clay indicators.

It is first necessary to make these indicators comparable by normalizing their variations. The normalized variation is obtained by dividing the variations by a normalization coefficient.

We first calculate, in each interval, the statistical maximum and minimum of each of the clay indicators k and the range of variation Dk equal to the difference between this maximum and this minimum.

The statistical maximum and minimum of a clay indicator k are the values xk1 and xk2 which give the maximum value to a function:

$$P_{(i)} = \sum_j \frac{\text{sign}\,(i,j)}{1+\alpha\left|x_i - x_j\right|^n} \qquad (17)$$

in which α is a positive coefficient and n a positive exponent. In general, we choose n=2.

The sign is the same as that of the difference $x_i - x_j$ for the calculation of the statistical maximum and the opposite of that of the difference $x_i - x_j$ for the calculation of the statistical minimum.

The variation range Dk of a clay indicator k in an interval is equal to xk2—xk1. The variations of the different indicators are normalized by dividing each of them by a normalization coefficient Nk whose absolute value is chosen such that the normalized variation range of each indicator is the same and equal to n units of variation.

Thus,

$$|Nk| = \frac{|Dk|}{n}$$

However, for each clay indicator, we set a minimum variation range λk, corresponding to n units. If the variation range of the said indicator is smaller than λk, we choose as the absolute value of the normalization coefficient

$$|Nk| = \frac{|\lambda k|}{n}$$

The normalization coefficient is assigned a positive sign if the corresponding clay indicator has a maximum value in the clay and a negative sign if the clay indicator has a minimum value in the clay.

For the indicator consisting of the diameter of the hole measured in inches, the value of the normalization coefficient is set equal to 0.5. If we use a normalized variation range equal to 30 units, the minimum values of λk for the other indicators are as follows: SP=60 mv; GR=75 API; ϕ_N.GR=30; ρ_{max}=0.45; N'=0.60; M=0.18; M'=0.42.

After this operation for normalizing the variations of the different clay indicators, we come to the operations for determining the most argillaceous level and the least argillaceous level of each interval.

For each level i of the interval, we calculate the function

$$P'(i) = \sum_j [F'(i,j).\text{sign}\ (i,j)]$$

where F'(i, j) is chosen as:

$$F'(i,j) = \frac{1}{1 + \alpha \sum_k \left| \frac{xk(i) - xk(j)}{Nk} \right|^n} \qquad (18)$$

and α is a positive coefficient and n a positive exponent, for example 1 or 2. $P'_{(i)}$ is the sum of the values of F'(i, j) when i is fixed and j takes on successively all the values of the interval, and sign (i, j) is assigned a value −1, 0 or 1 depending on the sign of the normalized variation defined below.

We choose as the most argillaceous level and as the least argillaceous level of each interval those which give the function P'(i) its maximum value.

The most argillaceous level or best clay zone is the one which gives the maximum value of the function P'(i) in which the following values are given to the sign expression (i, j):

$$+1 \quad \text{if} \quad \frac{xk(i) - xk(j)}{Nk} > 0 \quad \text{for every indicator k.}$$

$$0 \quad \text{if} \quad \frac{xk(i) - xk(j)}{Nk} < 0 \quad \text{for a single indicator k.}$$

$$-1 \quad \text{if} \quad \frac{xk(i) - xk(j)}{Nk} < 0 \quad \text{for several indicators k.}$$

The least argillaceous level or best clean zone is the one which gives the maximum value of the function P'(i) in which the following values are given to the sign expression (i, j):

$$+1 \quad \text{if} \quad \frac{xk(i) - xk(j)}{-Nk} > 0 \quad \text{for every indicator k.}$$

$$0 \text{ if } \frac{xk(i)-xk(j)}{-Nk} < 0 \text{ for a single indicator k.}$$

$$-1 \text{ if } \frac{xk(i)-xk(j)}{-Nk} < 0 \text{ for several indicators k.}$$

The determination of the most argillaceous level and the least argillaceous level is similar to the determination of the statistical maximum and the statistical minimum of all the values of a single indicator.

What is involved is determining the statistical maximum and minimum of the clay proportions furnished by several different indicators after having normalized the information furnished by these different indicators to make them comparable to each other.

Phase III_3: Determination of clay parameters

Having determined the most argillaceous level of each interval, we calculate the apparent matrix density ρ_{maa} of each of these levels according to the formula (12) and we consider the largest apparent density thus found, called $\rho_{ma\ max}$ and we designate the level and the interval to which it belongs as the pivot level and interval. It would also be possible to calculate other parameters for all the most argillaceous levels, for example the parameter M according to the formula (14).

Three cases are to be considered:

—If $\rho_{ma\ max} > 3$ or if corresponding $M < 0.65$, we consider that the pivot level is composed of pure clay and the parameters (ρ_{bCl}, ϕ_{NCl}, $R_{t\ Cl}$, SP_{Cl}, GR_{Cl} and Δt_{Cl}) corresponding to the pivot level are retained as values of the clay parameters for the entire pivot interval.

—If $\rho_{ma\ max} < 2.9$ and $M > 0.68$, we consider that throughout the studied geological stage, there is no sufficiently argillaceous formation to allow the valid calculations of the clay parameters and, in this case, the clay parameters must be taken from a file.

—If $2.9 < \rho_{ma\ max} < 3$ or if $0.65 < M < 0.68$, we assume that the apparent density of the pure clay in the pivot interval $\rho_{ma\ Cl} = 3$. From this value, and from the value of $\rho_{ma\ max}$ and the value of the apparent matrix density ρ_{ma} in the pivot interval, which is known, we calculate by linear interpolation the clay percentage V_{Cl} of the pivot level according to the approximate formula:

$$V_{Cl} = \frac{\rho_{ma\ max} - \rho_{ma}}{\rho_{maCl} - \rho_{ma}} \qquad (20)$$

Knowing the clay percentage of the pivot level, we derive the values of the clay parameters of this level, valid for the entire interval, by the different formulas which express the clay percentage as a function of the variations of a parameter. For example, we calculate GR_{Cl} by the formula:

$$V_{Cl} = \frac{GR - GR_{ma}}{GR_{Cl} - GR_{ma}} \qquad (21)$$

in which GR_{ma} is the gamma radioactivity in the matrix of the pivot interval, which is known.

Other parameters for the entire interval may be determined as follows: SP_{Cl} is set equal to the spontaneous potential measured at the pivot level. $R_{t\ Cl}$ is determined by:

$$V_{Cl} = \sqrt{\frac{R_{t\ Cl}}{R_t}} \qquad (24)$$

where R_t is resistivity reading at the pivot level. The value of ρ_{bCl} is computed from the value of ρ_b and ϕ_N at the pivot level and the neutron porosity measurement for the matrix rocks in the interval j, $\phi_{N\ ma}$.

$$\rho_{bCl}=\frac{\rho_b+F\,\rho_{ma}}{1+F} \quad (27)$$

where:

$$F=\frac{A.C(V_{Cl}-1)}{A.D-B\,V_{Cl}} \quad (28)$$

and

$$A=\rho_b-\phi_N-\rho_{ma}+\phi_N\,\rho_{ma} \quad (29)$$

$$B=(1-\phi_N)\,(\rho_{ma}-1)\,\phi_{N\,ma} \quad (30)$$

$$C=1-\phi_N \quad (31)$$

$$D=1-\phi_{N\,ma} \quad (32)$$

The neutron porosity of clay, $\phi_{N\,Cl}$, is found according to the formula:

$$\phi_{NCl}=\frac{\phi_N+F\,\phi_{N\,ma}}{1+F} \quad (33)$$

The acoustic transit time for clay, Δt_{Cl} is computed as:

$$\Delta t_{Cl}=\frac{\Delta t+F\,\Delta t_{ma}}{1+F} \quad (34)$$

where Δt is acoustic transit time for the pivot level and Δt_{ma} is the acoustic transit time for the matrix rocks in the interval.

—For each of the intervals other than the pivot interval, we consider the value of the apparent density $\rho_{ma\,Cl1}$ calculated for the most argillaceous level of the interval.

Two cases are to be considered:

—If $\rho_{ma\,Cl1}>3$ and $\rho_{ma\,Cl1}>\rho_{ma\,max}-0.05$ whichever is larger, $\rho_{ma\,max}$ being either the value found for the pivot level if this value is higher than 3, or 3 in the opposite case, we consider that the corresponding level is composed of pure clay and the parameters for the corresponding interval are taken as being equal to the value at this level.

If the preceding condition is not met, we calculate the clay percentage $V_{Cl\,1}$ of the most argillaceous level of the interval by linear interpolation, assuming that the apparent density of the clay of this level is the one which was found for the pivot level $\rho_{ma}Cl_{max}$ and by using the known apparent matrix density of the corresponding interval ρ_{ma}:

$$V_{Cl\,1}=\frac{\rho_{ma}\,Cl_1-\rho_{ma}}{\rho_{ma}\,Cl_{max}-\rho_{ma}} \quad (22)$$

If the value of $V_{Cl\,1}$ this calculated is higher than 0.60, it is considered that the corresponding level is sufficiently argillaceous to allow the calculation of the values of the valid clay parameters.

These parameters, valid for the entire interval, are computed as before for the pivot level, from the known formulas expressing the clay percentages as a function of the different parameters.

By contrast, for the spontaneous potential, we use as the value of the spontaneous potential in the clay SP_{Cl}, valid for the entire interval, the value measured for the most argillaceous level of the interval because, beyond a clay content 0.60, the spontaneous potential remains substantially constant.

If the clay proportion of the most argillaceous level of an interval is smaller than 0.60, we consider that there is no sufficiently argillaceous level in the interval to allow a valid computation of the clay parameters and, in this case, the clay parameters of the

interval are computed by the linear interpolation of the values of the clay parameters of the intervals located on either side. If what is involved is an interval located at one end of the geological stage, we choose as the values of the clay parameters of this interval those of the adjacent interval.

Determination of V_{Cl} from GR:

The purpose of the Phase III_s is also to provide a first approximate evaluation of the clay proportion V_{Cl} contained in each level.

It is known that an approximate upper limit of the clay proportion $V_{Cl\ (i)}$ of the natural gamma radioactivity of this level by linear interpolation from gamma radioactivity values in the pure clays, is GR_{Cl} and in the formations without clay, GR_o, according to the formula (5).

The following technique makes it possible to determine with good accuracy the values of GR_o and GR_{Cl} along the borehole.

We consider all the values of GR measured for all the least argillaceous levels of each interval. We determine the smallest of these values, that is GR_{min}.

Likewise, we consider all the values of GR measured for all the most argillaceous levels of each interval and we calculate the largest of these values, namely GR_{max}.

We use these values GR_{min} and GR_{max} to determine over the entire borehole the reference lines of the values of GR_{Cl} and of GR_o. We first look for all the intervals for which the measured value of GR remains statistically stable over a thickness of at least 10 feet or 3 meters. We consider this condition to be fulfilled if the standard deviation, σ, remains smaller than a limit, for example

$$\frac{\sqrt{GR}}{2}$$

If this stable value is near the value GR_{min}, we consider the said thickness as a formation without clay and the corresponding value of GR as a measurement of GR_o.

If this stable value is near GR_{max}, we consider the stable value GR as a measurement of GR_{Cl}.

For example, we consider that the values of GR which are higher than GR_{min} by an amount smaller than one-fifth of the deviation between GR_{max} and GR_{min} correspond to clean formations, that is $GR_{(i)}=GR_o$ if:

$$GR_{(i)}-GR_{min}<0.2\ (GR_{max}-GR_{min})$$

Likewise, we consider that the values of GR which deviate from GR_{max} in either direction, by an amount smaller than one-fifth of the difference between GR_{max} and GR_{min} correspond to pure clay, that is:

$GR_{(i)}=GR_{Cl}$ if:

$$0.8\ (GR_{max}-GR_{min})<GR_{(i)}-GR_{min}<1.2\ (GR_{max}-GR_{min})$$

If, in an interval, there is no stable value of GR sufficiently close to GR_{min} and GR_{max}, then GR_{min} and GR_{max} are used as values of GR_o and GR_{Cl}.

We determine the continuous reference lines of the values of GR_o and of GR_{Cl} in the following manner:

The lowest of the values of GR_{Cl} is extended on either side up to the next stable value of GR_{Cl}. Then, the same is done for the value of GR_{Cl} immediately above and so on until we have obtained a continuous step line over the entire length of the borehole, which serves as the reference line for the values of GR_{Cl} in the argillaceous formations.

In the same manner, we determine a continuous reference line or baseline of the values of GR_o corresponding to the clean formations.

We first extend each section corresponding to GR_o over the entire extent of a permeable bed whose limits are defined by constant readings of SP equal to the readings in the clay.

In the same manner, the continuous line of GR_o is obtained by combining the voids beginning with the smallest value of GR_o.

For each level (i) it is thus possible to calculate $V_{Cl\ (i)}$ using the values of GR_o and GR_{Cl} given by the two reference lines thus determined.

Determination of V_{Cl} from SP

An approximate upper limit of the clay proportion contained in a level (i) can also be derived from the measurement of the spontaneous potential in the said level $SP_{(i)}$ by linear interpolation from, on the one hand, the values of the spontaneous potential in the clay SP_{Cl} which constitute the base line and, on the other, in the clean formations, and this is called the static spontaneous potential or SSP.

The formula used in the following:

$$V_{Cl}=\frac{SP-SSP}{SP_{Cl}-SSP} \qquad (19)$$

Whenever the measurement SP remains statistically constant, the standard deviation σ being lower than 0.5 mv over at least 8 feet or 2.50 meters or lower than 1.2 mv over at least 16 feet or 5 meters, we consider that the measurement corresponds to the base line or to the static spontaneous potential. For each of these sections, we calculate the apparent matrix density ρ_{maa} by the formula (12) and we compare the value found with the density of the clay $\rho_{ma\,Cl}$ previously calculated. If the difference $\rho_{ma\,Cl}-\rho_{maa}$ is near zero, for example, lower than 0.05 and if, at the same time, the clay proportion V_{Cl} GR calculated from the measurements of GR is greater than 50%, we consider the corresponding value of SP to be the measurement of SP in the clay SP_{Cl}.

To be on the safe side, it is possible to add other conditions, for example the condition that the value of the indicator M should be lower than 0.70.

If, on the contrary, $\rho_{ma\,Cl}-\rho_{maa}>0.30$ and if V_{Cl} GR$<$20%, the corresponding value of SP is considered to be a measurement of SSP.

The base line of the spontaneous potential in the argillaceous formations is the broken line which connects all the middles of the segments identified as corresponding to SP_{Cl}.

The reference line for values of SSP is determined by extending the SSP value for each section over the entire extent of a permeable bed whose limits are defined by two clay beds on opposite sides of the permeable bed. The clay beds are described as having constant SP readings equal to the readings in clay. This is the same procedure as used in extending the base line for GR_c. The voids between the SSP base line are filled in as described above.

The deflections of the static spontaneous potential, i.e., the deviations between the value of the static spontaneous potential and the base value of the spontaneous potential, are read from the base line thus plotted. For the evaluation of the clay percentage, consideration is given only to the intervals in which the deflections of SSP are negative and smaller than -30mv.

In conclusion, Stage III makes it possible to calculate for each interval an approximate value of the clay parameters, in particular of the clay density $\rho_{b\,Cl}$, clay neutron porosity $\phi_{N\,Cl}$, clay resistivity $R_{t\,Cl}$, natural gamma radiation GR_{Cl} in the clay, spontaneous potential in the clay SP_{Cl}, and acoustic transit time in the clay Δt_{Cl}. These values are used as input values in a more detailed program which has already been described in earlier patent applications.

Stage III also makes it possible to determine relatively accurate values of the parameters GR_c and SSP corresponding to the levels without clay and, from these values, to calculate the clay proportion V_{Cl} in each level.

On the basis of this calculation, it is possible to determine the low clay levels which are used in Stage IV to calibrate the instruments for the measurement of neutron porosity ϕ_N and bulk density ρ_b.

Figs. 6 and 7 represent the flow chart of the operations which constitute Stage III.

Phase III_1:

Block 44 represents the calculations making it possible to calculate the correlation coefficient of each variable parameter x_i with each of the other parameters y_j over the extent of a geological stage.

For each of the parameters k, we calculate, for all the levels i of a geological stage:

1) the sum $\Sigma_i\, x_{(i)}$ of the values of the said parameter.
2) the sum $-_i\, x^2_{(i)}$ of the squares of the values of the said parameter.

3) the sum $\Sigma_i x_{(i)} \cdot y_{(i)}$ of the products of the values taken on by the said parameter multiplied by the values $y_{(i)}$ taken on by each of the other parameter.

4) the average $\bar{x}$ of all the values of each parameter and the square $\bar{x^2}$ of this average.

A loop 44a is made for each indicator k. These sums and averages make it possible to calculate correlation coefficients between two parameters according to the formula (16).

The term $\Sigma_i (x_i - \bar{x})^2$ which appears in the formula (16) and which is the sum of the standard deviations is equal to:

$$\sum_i x_i^2 - 2n\,\bar{x}.\Sigma_i x_i + n\,\bar{x^2}$$

Block 45 represents the calculation of the correlation coefficient of each parameter k in relation to each of the other parameters.

Block 46 represents the calculation of the sum of the absolute values of the correlation coefficients of each parameter in relation to each of the others.

Block 47 represents the selection of the pivot indicator, i.e., that of the parameters whose sum calculated by the block 46 has a maximum value, and also the selection of the second best indicator and of the clay indicators which will be adopted for the rest of the processing.

Block 48 represents the determination of the sign of the polarity SP.

Phase III_1 is completed.

Phase III_2:

Block 49 represents the calculation of the statistical maximum of all the values of each clay indicator xk and the block 50 the calculation of the statistical minimum of all the values of each indicator.

This maximum and this minimum are the values which correspond to the level i_1 and i_2 for which the function of equation (17),

$$P_{(i)} = \sum_j \frac{\text{sign}\,(i,j)}{1+\alpha|x_i - x_j|^n}$$

has a maximum value.

We choose n=2 for example. The value of α varies dependent upon the formation. In practice, three different values of α are chosen, for example 2.10^{-4}, 2.10^{-3} and 2.10^{-2}, allowing the calculation of three statistical minimums or maximums and we then take the average of the three values thus calculated.

The value of the sign is equal to or opposite that of the different $x_i - x_j$ depending on whether the maximum or the minimum is sought.

Block 51 represents the calculation of the absolute value of the variation range |Dk| of each indicator which is the difference between the values determined by the blocks 49 and 50.

Block 52 represents the comparison of |Dk| with the minimum variation range |λk| corresponding to 30 variation units.

If $|Dk| \leq |\lambda k|$, the absolute value of the normaliaztion coefficient |Nk| is calculated by the block 53 according to the formula

$$|Nk| = \frac{|\lambda k|}{30}.$$

If, on the other hand, |Nk| is greater than |λk|, the block 54 calculates an absolute value of the normalization coefficient.

$$|Nk| = \frac{|Dk|}{30}.$$

The flow chart includes a loop 55 for each clay indicator.

Phase III_2 is then pursued for the determination of the most argillaceous levels and the least argillaceous levels.

Each geological stage is divided into intervals of a given thickness, for example into intervals of 250 feet and we determine the most argillaceous level and the least argillaceous level for each interval.

For each interval, we read the information level by level (block 56).

Cuts are made to eliminate all the levels corresponding to anhydrite, salt, coal or compact formations which were determined during stage II. We also eliminate the levels corresponding to values of GR higher than a limit, for example 150 API units and the levels for which the porosity measured by the neutron probe is low.

For example, we take only the levels for which $\phi_N > 10$ porosity units.

Likewise, we take only the levels for which the ratio R_{xo}/R_t is between certain limits, for example between 0.5 and 2.

Block 57 represents these eliminations.

Block 58 represents the storage of the adopted information. Owing to the abundance of this information, only one information item out of two is stored in order to reduce the calculations.

Block 59 determines, after each level, whether the thickness of the interval considered is reached. If not, block 60 determines whether the limits of the considered geological stage have been reached. If this is not the case, we form a loop 61 to go on to the next level.

If blocks 59 and 60 determine that the limits of the interval or of the geological stage are reached, the reading of information relative to an interval is terminated and the program is pursued by calculating the statistical optima of the considered interval. The flow chart of this calculation is shown in Fig. 7.

For each level i of the interval, we determine the value of the function $P'_{(i)}$ and we determine for which level i the fuuction $P'_{(i)}$ has a maximum value. The calculation is substantially the same for determining the most argillaceous level and the least argillaceous level.

In both cases, we look for the maximum of a function:

$$P'_{(i)} = \sum_j F'_{(i,j)} \text{ sign } (i,j)$$

where $F'_{(i,j)}$ is given by Equation 18.

We then go from the calculation of the most argillaceous level to the calculation of the least argillaceous level by modifying only the value of the sign NK.

Fig. 7 represents the calculation of the most argillaceous level.

Block 62 represents the values at the beginning of the interval. The function $P'=0$.

S.M. represents an index which corresponds to the number of times the expression Dk/Nk is negative. Dk/Nk is the normalized variation of an indicator.

We consider two levels i and j of the interval and a clay indicator k.

We first calculate the difference $xk_{(i)} - xk_{(j)}$, that is the difference between the values of the indicator k for the levels i and j (block 63).

We then calculate the normalized variation

$$\frac{Dk_{(i,j)}}{Nk} = \frac{xk_{(i)} - xk_{(j)}}{Nk} \text{ (block 64).}$$

Block 65 determines whether the normalized variation is positive or negative.

If it is negative, block 66 calculates the absolute value

$$\left|\frac{Dk}{Nk}\right| = -\frac{Dk}{Nk}.$$

(The operation of block 70 will be explained below).

If it is positive

$$\left|\frac{Dk}{Nk}\right| = \frac{Dk}{Nk} \qquad \text{(block 67).}$$

Block 68 calculates the new partial sum:

$$\sum_k \frac{|Dk|}{Nk} = \sum'_k + \frac{|Dk|}{Nk}$$

that is, block 68 adds to the preceding value $\sum'_k$ the value

$$\left|\frac{Dk}{Nk}\right|$$

furnished by block 66 or block 67.

A loop 69 is made to take into account the values corresponding to the levels i and j furnished by all the indicators k. When the loop is completed, block 68 furnishes

$$\sum_k \left|\frac{Dk}{Nk}\right|$$

corresponding to the two levels i and j.

It is thus possible to compute the function:

$$F'(i,j) = \frac{1}{1 + \alpha \sum_k \left|\frac{Dk}{NK}\right|^n} \qquad (18')$$

by choosing for α a positive value, for example 1 and for n, a positive value, for example 1. It is seen that Equation 18′ is Equation 18 in rewritten form.

We next have to compute:

$$P_{(i)} = \sum_j \left[F'(i,j) \cdot sign\ (i,j)\right].$$

If block 65 has determined that

$$\frac{Dk}{Nk} < 0$$

block 70 calculates a new value of SM=SM′+1, SM′ being the preceding value.

Once the loop 69 has been completed for all the indicators k, we obtain a total value of $SM_{(i,j)}$ for the two levels i and j.

Block 71 determines whether this value is equal to 0, to 1 or is higher than 1.

If $SM_{(i,j)}=0$, that is for every k,

$$\frac{Dk}{Nk} > 0$$

sign (i,j)=+1 (block 72).

If $SM_{(i,j)}=1$, that is, if there is one indicator k and only one for this Dk/Nk<0, sign (i,j)=0 (block 73).

If $Sm_{(i,j)}>0$, sign (ij)=−1 block 74).

In the case where the least argillaceous level is sought, we replace Nk by −Nk and we record, in the same manner, Dk/−Nk<0, and the sign of (i,j) is determined in the same manner.

Knowing the value of sign (i,j) and of the function:

$$F'(i,j) = \frac{1}{1 + \alpha \sum_k \left|\frac{Dk}{Nk}\right|^n}$$

we compute the product $F'_{(i,j)}$ sign (i,j)

We compute each time a new partial sum: $\Sigma = \Sigma' + F'_{(i,j)} \cdot sign\ (i,j)$ (block 75), Σ' being the preceding value.

We then make a loop 76 for each of the levels j of the interval.

When all the intervals j have been taken into account, the sum represents:

$$P_{(i)} = \sum_j \left[F'(i,j) \cdot sign\ (i,j) \right] .$$

Block 77 compares this sum $P'_{(i)}$ with the maximum values of the same sum found previously.

If this value is smaller, it need not be recorded, and the program forms a loop 78 to scan all the levels i of the interval.

If the value $P'_{(i)}$,

$$P_{(i)} = \sum_j \left[F'(i,j) \cdot sign\ (i,j) \right] .$$

is higher than the previously found maximum, it is recorded.

At the end of an interval, the level which corresponds to the maximum of $P'_{(i)}$ is the most argillaceous level or the least argillaceous level of the interval and it is retained (block 79).

The program then executes a loop 80 for the next interval, and then a loop 81 for the next geological stage, returning to block 44, Fig. 6.

The program is then pursued for the study of the stability of the gamma radioactivity, of the spontaneous potential and of the clay parameters. The flow chart of these operations which constitute phase III_s is shown in Fig. 8.

Referring now to Fig. 8, phase III_s is entered via block 150. The apparent matrix density ρ_{ma} and the parameter M is computed using equations 12 and 14 respectively, for the most argillaceous level in each interval, block 152. Next, the largest of the apparent densities is selected and called $\rho_{ma\ max}$, block 154. The level at which $\rho_{ma\ max}$ is found is designated the pivot level and the interval containing that level is designated the pivot interval.

The parameters for the pivot interval are now computed. To this end, decision element 156 asks if $\rho_{ma\ max}$ is greater than 3 or whether M is less than 0.65. If it is the level is considered to be composed of pure clay and the values of the parameters for the pivot level (ρ_b, ϕ_N, R_t, SP, GR, Δt) are retained as the clay parameters for the entire pivot interval, block 158. If the answer is NO, decision element 160 asks if $\rho_{ma\ max}$ is less than 2.9 and whether M is greater than 0.68. If the answer is YES, predetermined values of the parameters are utilized as clay parameters for the interval, block 162.

If the answer from decision element 160 is NO, the clay parameters for the interval must be computed. To this end, $\rho_{ma\ cl}$ is set equal to 3, block 164. From block 164, the program proceeds to block 166 where the clay percentage is computed for the pivot level using equation 20. Next, the clay parameters valid for the entire pivot interval are determined. First SP_{cl} is set equal to the value of SP of the pivot level. Then GR_{cl}, $R_{t\ cl}$, $\phi_{N\ cl}$, $\rho_{b\ cl}$ and Δt_{cl} are computed using equations 21 and 26—34. This operation is represented by block 168.

Either from blocks 158, 162 or 168, the program proceeds to block 172 where the operation of computing the clay parameters for the other intervals is begun. For the most argillaceous level in each interval, the apparent matrix density, $\rho_{ma\ cll}$ is computed using equation 12, block 172. Decision element 174 next asks if $\rho_{ma\ cll}$ is greater than 3 and if $\rho_{ma\ cll}$ is greater than $\rho_{ma\ max}$—0.05 and if it is, the parameters for the interval are set equal to the parameters for the most argillaceous level in the interval, block 176.

If the answer from decision element 174 is NO, the value of V_{cl} for the most argillaceous level, V_{cll} is computed using equation 22, block 177 after which decision element 178 asks if V_{cll} is greater than 0.60 and if it is, the values for the clay parameters are computed using Equations 21 and 26—34, block 180 and the value of SP_{cl} is set equal to the value of the SP at the most argillaceous level in the interval, block 182. If the answer from decision element 178 is NO, decision element 184 asks if the interval under consideration is at one end of a geological stage. If it is, the clay parameters for the interval are set equal to those of the adjacent interval, block 176 and

if it is not, the clay parameters are computed by linear interpolation between the intervals on either side of the interval under study, block 188.

After each interval is processed, decision element 190, asks if this is the last interval and if it is not, the program returns to block 172 to compute the parameters for the next interval. After all the intervals have been processed, YES answer from decision element 190, the program next determines a value of V_{cl} for each depth level using the gamma ray measurements. To this end, the minimum GR, GR_{min} measured for all the least argillaceous levels and the maximum GR, GR_{max}, for all the most argillaceous levels is determined, blocks 192 and 194 respectively. Next, sections of the interval are selected for which the GR does not vary by more than $\pm$

$$\frac{\sqrt{GR}}{2}$$

block 196. These values are called GR_1.

Next decision element 198 asks if the difference between GR_1 and GR_{min} is less than 0.2 ($GR_{max}-GR_{min}$) and if it is, the value of GR in sands, GR_o is set equal to GR_1, block 200. If the answer from decision element 198 is NO, decision element 202 determines if GR is near GR_{max} and if it is, GR_{cl}, GR in clay is set equal to GR_1. If the answer from decision element 202 is NO, GR_o and GR_{cl} are equal respectively to GR_{min} and GR_{max}, block 204. If this is not the last interval, NO answer from decision element 206, the program returns to block 196 for processing of the next interval.

After all the intervals have been processed, baselines for GR_o and GR_{cl} are established. The baseline for GR_{cl} is established by first assigning the value of GR_{cl} computed for the lowest depth level for all depth levels from the lowest depth level in the formation up to the depth level at which the next stable value of GR_{cl} is computed. Then the next stable value of GR_{cl} is assigned to all depth levels up to the depth level at which the next stable value of GR_{cl} is computed and so on until a value of GR_{cl} is assigned to all depth levels of interest. This is represented by block 208.

The baseline for GR_o is established by assigning values of GR_o to all depth levels in a section of the borehole corresponding to a permeable bed in which the value of GR is computed. The permeable bed can be defined as being bounded on either side by clay beds in which there are constant readings of SP. The value of GR_o for the depth levels in the remainder of the formation are then set using the same procedure as that described above for setting the baseline of GR_{cl}. This operation is represented by block 210.

Knowing the value of GR_o and GR_{cl} for each depth level, the value V_{cl} can be computed for each depth level using equation 5, block 212.

The proportion of clay at each depth level can also be determined from the spontaneous potential measurements from knowledge of SP_{cl} and SSP at each depth level. To determine the SSP and the SP_{cl} of each depth level, a borehole interval having a statistically constant SP is selected, as represented by block 214. Next, for the interval, the values of the apparent matrix density ρ_{maa}, designated $\rho_{maa\ SP}$ is computed using equation 12, block 216. Then decision element 218 asks if the difference between ρ_{maa} SP and $\rho_{ma\ cl}$ previously computed for the interval is small, i.e. less than 0.05 and if the proportion of clay computed using the GR measurement, $V_{cl(GR)}$ is greater than 50%. If it is, SP_{cl} is set equal to the measured value SP, block 220. If the answer is NO, decision element 222 asks if the difference between $\rho_{ma\ cl}$ and $\rho_{maa\ SP}$ is greater than 0.30 and if $V_{cl(GR)}$ is less than 20%. If the answer is YES, SSP is set equal to SP, block 224. The analysis of one section of constant SP is complete and decision element 226 asks if this is the last section. If it is not, the program returns to block 214. After all sections have been considered, YES answer from decision element 226, the baselines of SP_{cl} and SSP are set.

For the SP_{cl} baseline, the values of SP_{cl} at depth levels located between the depth levels at which SP_{cl} has been set according to block 220 are computed by considering the values of SP_{cl} set by block 220 for the depth levels immediately above and below the depth level of interest and using linear interpolation to find the value of SP_{cl} at the depth level of interest, block 228. The values for SSP are set as described for setting the values of GR_∞ as represented by block 230. Then the proportion of clay from the SP measurements, $V_{cl(SP)}$ is computed using equation 19 for those depth levels where SSP is less than -30 millivolts, block 232. After which the program goes to stage 4, block 234.

Stage IV—Calibration in water-bearing formations

The purpose of this stage is to calibrate the instruments used for measuring porosity ϕ_N and density ρ_b, using the measurements obtained in the water-bearing and low-clay formations, this calibration completing the one made in the compact formations and possibly in the levels of anhydrite and salt.

To perform this calibration, we compare the porosity reading ϕ_N with the porosity ϕR_t calculated from the true resistivity measurements by the formula (7):

$$\phi R_t = \sqrt[n]{\frac{a \cdot R_w}{R_t}}$$

To perform the calculation of ϕR_t, it is necessary to know R_w: the resistivity of water contained in the pores of the formations.

Two cases can arise.

In the first case, we know a value R_{wa} sufficiently close to R_w and we shall then make R_w vary around R_{wa}. If R_w is not known, even approximately, we calculate a first approximate value, R_{w1}, from the static spontaneous potential SSP by the formula:

$$SSP = -k \log \frac{R_{mf}}{R_{w1}} \qquad (23)$$

in which R_{mf} is the resistivity of the mud filtrate.

We calculate a second approximate value, R_{w2}, from the maximum value of the ratio R_{xo}/R_t by the formula:

$$\text{maximum } \frac{R_{xo}}{R_t} = \frac{R_{mf}}{R_{w2}} \qquad (24)$$

where the maximum

$$\frac{R_{xo}}{R_t}$$

isde termined by computing the statistical maximum of the value

$$\frac{R_{xo}}{R_t}$$

for each depth level.

We choose as an approximate value R_w', the smallest of the two values R_{w1} and R_{w2} and we make R_w vary around R_w' taking into account variation in R_w due to the increase in temperature with depth.

We calibrate by using only the data relative to the low-clay, water-bearing levels, which lead to the most reliable measurements.

We eliminate all the levels corresponding to compact formations, to large hole diameters and to fast variations in measurements with depth.

We keep only the sections for which the deviation of the measurement of spontaneous potential in relation to the base line of SSP is small, smaller than 10 or 15 mv and for which, at the same time, the clay content calculated from the measurement of SP ($V_{Cl}SP$) as well as the clay content calculated from the measurement of GR($V_{Cl}GR$) are smaller than 20%.

For all these levels, we calculate an approximate value of the resistivity of the formation water, R_{wa} ND, by the formula taken from formula 7:

$$R_{wa\ ND} = \frac{1}{a} \cdot (\phi_{ND})^n R_t \qquad (25)$$

in which ϕ_{ND} is the porosity measured on the graph of ϕ_D as a function of ϕ_N by inter-

polation between the two curves corresponding to the end matrices (see Fig. 1) and can be computed as:

$$\phi_{ND} = \phi_N + 0.03 \left[\frac{2.71-\rho_{maa}}{0.06}\right] \qquad (25')$$

for $\rho_{maa}<2.71$, or

$$\phi_{ND} = \phi_N - 0.03 \left[\frac{\rho_{maa}-2.71}{0.16}\right] \qquad (25'')$$

for $\rho_{maa}\geq 2.71$.

We calculate the statistical minimum $R_{wa}ND_{min}$ of all the values of $R_{wa}ND$ thus calculated.

We retain for the subsequent calibration only the levels for which the resistivity $R_{wa}ND$ is in the neighbourhood of this minimum, for example, all the points for which $R_{wa}ND<2\ R_{wa}ND_{min}$, which are clean levels, without hydrocarbons, if $R_{wa}ND_{min}$ is lower than or not much higher than R_{wa}.

This set of levels can be classified in terms of increasing clay percentage and if the number is high, for example, higher than 100, we use only the first 100.

We use these points to calibrate the neutron probe which measures the porosity ϕ_N and the measuring tool for density ρ_b by successively optimizing several functions.

During a first stage, we consider a function F which depends on the difference between the following two values of porosity:

1) The value ϕ_{Nc} indicated by the neutron probe after correction d ϕ_N, that is $\phi_{Nc}=\phi_N+d\ \phi_N$.

The value of ϕ_{Nc} thus depends on d ϕ_N.

2) The value $\phi\ R_t$ calculated by the formula (7):

$$\phi\ R_t = \sqrt[n]{\frac{a\cdot R_w}{R_t}} \qquad (7)$$

from the measurement of R_t and the value of R_w. This value $\phi\ R_t$ thus depends on R_w.

We compare the difference $\phi_N R_t=\phi_{Nc}-\phi\ R_t$ with the known values of the porosity of the two end matrices $\phi_{N\ ma1}$ and $\phi_{N\ ma2}$ with $\phi_{N\ ma1}<\phi_{N\ ma2}$.

We make R_w vary step by step around the approximate value R_{wa} or R_w' previously calculated. For example, we take a series of values equal to k R_w', the coefficient k varying between 0.5 and 2, in steps of 15% approximately.

Likewise, we give d ϕ_N a series of values located on either side of zero. For example, we make d ϕ_N vary in steps equal to 1 porosity unit between −8 porosity units and +8 porosity units.

To each pair of values k R_w' and d ϕ_N, there corresponds, for a given level i a value of the difference $\phi_N R_{t(i)}$.

We calculate a function $F_{(i)}$ of $\phi_N R_{t(i)}$ having the following values:

$F_{(i)}=-1$ if $\phi_N R_{t(i)}<\phi_{N\ ma1}$.

$F_{(i)}=+1$ if $\phi_{N\ ma1}<\phi_N R_{t(i)}<\phi_{N\ ma2}$.

$F_{(i)}=0$ if $\phi_{N\ ma2}<\phi_N R_{t(i)}$.

For each pair of values d ϕ_N and k R_w', we take the sum $\sum_i F_{(i)}$ for all the water-bearing and low-clay levels chosen.

We calculate the sum $\sum_i F_{(i)}$ for all the possible pairs of values of d ϕ_N and k R_w'.

Once the calculations are completed, we note the pair of values which corresponds to the maximum of $\sum_i F_{(i)}$. We designate this pair of values by the symbols A for d ϕ_N and R_{waN} for k R_w'.

Two cases can occur.

In a first case, we do not obtain a clear maximum, i.e., the maximum value of $\sum_i F_{(i)}$ is obtained for end values d ϕ_N or k R_w', or the obtained maximum is low in relation to the maximum value at the limits, for example lower than 1.5 times this value at the limits. In these two cases, it is considered that there is no precise maximum.

In a second case, on the other hand, we obtain a very clear maximum of $\sum_i F_{(i)}$ for a pair of values $d\phi_N = A$ and R_{waN} from the limits.

In this second case, we select the levels (j) for which $F_{(j)} = +1$ when $d\phi_N = A$ and $k R_w' = R_{waN}$.

We calculate, for each level (j) a value $\rho_{ma}R_{t(j)}$ of the matrix density by a formula similar to the formula (9):

$$\rho_{ma} R_{t(j)} = \frac{\rho_{bo} - \phi R_t \rho_{mf}}{1 - R\phi_t} \qquad (9')$$

$\rho_{bo} = \rho_b + d\rho_b$ that is ρ_{bo} is the value of ρ_b corrected by a quantity d ρ_b.

ρ_{mf} is the known density of the mud filtrate contained in the pores of the formations.

ϕR_t is the value of the porosity calculated by the formula (7).

$\rho_{ma} R_t$ is thus a function of R_w and of d ρ_b. Like before, we make R_w and d ρ_b vary step by step. For example, we choose for d ρ_b a series of values between −0.06 and +0.06 between which it varies in steps equal to 0.01.

We calculate a function $F'_{(j)}$ of $\rho_{ma} R_{t(j)}$ having the following values:

$F'_{(j)} = +1$ if $\rho_{ma1} < \rho_{ma}R_{t(j)} < \rho_{ma2}$.

$F'_{(j)} = -1$ if $\rho_{ma}R_{t(j)} < \rho_{ma1}$

or $\rho_{ma}R_{t(j)} > \rho_{ma2}$.

ρ_{ma1} and ρ_{ma2} are the densities of the end matrices traversed by the borehole.

For each pair of values R_w and of d ρ_b we compute the sum $\sum_j F'_{(j)}$ for all the levels j selected.

We note the maximum of $\sum_j F'_{(j)}$ and the corresponding values of $R_w = R_{waD}$ and of $d\rho_b = B$.

If R_{waD} is close to R_{waN}, for example, $R_{waD} - R_{waN} < \pm(0.15\ (R_{waN})$, a calibration by a simple scale shift of ϕ_N is valid.

In this case, we compute a new value of the matrix density by a formula similar to the formula (12):

$$\rho_{maN(j)} = \frac{\rho_{bo} - \phi_{No}\rho_{mf}}{1 - \phi_N} \qquad (12')$$

The value of $\rho_{maN(j)}$ depends on the values of $d\rho_b$ and $d\phi_N$ which are made to vary step by step around zero as previously.

We consider the levels j selected previously and we calculate a function $F''_{(j)}$ of $\rho_{maN(j)}$ having the following values:

$F''_{(j)} = +1$ if $\rho_{ma1} < \rho_{maN(j)} < \rho_{ma2}$

$F''_{(j)} = -1$ if $\rho_{maN(j)} < \rho_{ma1}$

or $\rho_{maN(j)} > \rho_{ma2}$.

For each pair of values of $d\phi_N$ and of $d\rho_b$ we calculate the sum $\sum_j F''_{(j)}$.

What is generally obtained is a series of maxima of $\sum$ corresponding to values of $d\phi_N$ and of $d\rho_b$ related to each other by a linear relationship.

We choose as the values for zero shift correction for the porosity and density

measurements the maximum which corresponds to the pair of values $d\phi_{Nm}$ and $d\rho_{bm}$ closest to $d\phi_N=A$ and $d\rho_m=B$.

The corrected measurements used for the following operations are thus:

$$\phi_{No}=\phi_N+d\,\phi_{Nm}.$$

$$\rho_{bo}=\rho_b+d\,\rho_{bm}.$$

Of course, if the value R_w of the formation water resistivity is known accurately, the values of $d\,\rho_b$ and of $d\,\phi_N$ corresponding to R_w are chosen.

If the difference between the values of R_{waD} and of R_{waN} is not small, a simple zero shift correction is not sufficient and it is necessary to introduce a sensitivity multiplying factor C into the correction of the measurement of porosity ϕ_N.

This factor C is made to vary step by step, for example in steps equal to 0.1, between the values 0.7 C_o and 1.4 C_o with

$$C_o=\sqrt[n]{\frac{R_{waD}}{R_{waN}}}.$$

A first value of the matrix density $\rho'_{maN(j)}$ is calculated by the formula:

$$\rho'_{maN(j)}=\frac{\rho_{bO}-C.\phi_N.\rho_{mf}}{1-C.\phi_N} \qquad (12'')$$

The value $\rho'_{maN(j)}$ depends on the values of $d\,\rho_b$ and C.

All the levels j are still considered and we calculate the function $F''_{(j)}$ equal to $+1$ if $\rho'_{maN(j)}$ is between the end matrix densities ρ_{ma1} and ρ_{ma2} and equal to -1 in the opposite case.

For each pair of values of C and of $d\,\rho_b$ we calculate $\sum_j F''_{(j)}$.

We note the maximum of Σ and the value of C, called C_m, which corresponds to this maximum.

We again calculate the matrix density:

$$\rho_{maN(j)}=\frac{\rho_{bo}-\phi_{No}.\rho_{mf}}{1-\phi_{No}} \qquad (12''')$$

with $\phi_{No}=C_m(\phi_N+d\,\phi_N)$. We make $d\,\rho_b$ and $d\,\phi_N$ vary step by step. We calculate for each pair of values the $F''_{(j)}$ whose value is equal to $+1$ if $\rho_{maN(j)}$ is between ρ_{ma1} and ρ_{ma2} and to -1 in the opposite case. We take the sum of $\sum_j F''_{(j)}$ and we note the maximum or maxima of this sum. Generally, we obtain a series of maxima which are aligned. We choose the maximum which corresponds to a pair of values $d\,\phi_{Nm}$ and $d\,\rho_{bm}$ closest to $d\,\phi_N=A$ and $d\,\rho_b=B$ and we choose these values as shift values to be applied to the measurements of ϕ_N and of ρ_b.

The corrected measurements thus become:

$$\phi_{No}=C_m.(\phi_N+d\,\phi_{Nm})$$

$$\rho_{bo}=\rho_b+\rho_{bm}.$$

In the case where the study of the sum $\sum_j F_{(j)}$ has not allowed a very clear maximum to be found, we select the levels j' which lead to $F_{(j')}=+1$ when the estimated value R_w' is given to R_w.

We then look for the pair of values of $d\,\rho_b$ and $d\,\phi_N$ which optimize the function $\sum_j F''_{(j')}$ with $F''_{(j')}$ equal ± 1 depending on whether the value of $\rho_{maN(j')}$ calculated by formula (12) is located between ρ_{ma1} and ρ_{ma2} or not.

A family of maxima is generally obtained.

If a sufficiently reliable value of R_w is known, we choose $R_{waN}=R_w$, then the value

$d\phi_{Nm}$ which, associated with R_w, leads to the maximum of $\sum_i F_{(i)}$ and then the value $d\rho_{bm}$ which, associated with $d\phi_{Nm}$, leads to the maximum of $\sum_{i'} F''_{(i)}$.

A correction $d\rho_b$ greater than 0.05 is improbable. If higher values are found, we choose a correction $d\rho_{bm}=0.05$ and the corresponding correction $d\phi_{Nm}$.

In the case where, during stage II, a calibration has been made in the low-porosity formations, the corrections $d\phi_N$ and $d\rho_b$ are smaller and we limit the search for optima by varying $\Delta\rho_b$ and $\Delta\phi_N$ step by step between ± 0.02 only.

Once these calibrations have been made, we know an approximate value of R_w, which is the value $R_{waN}=R_{waD}$ corresponding to the values of $\phi_{N\,cor}$ and $\rho_{b\,cor}$.

We recalculate the values of ρ_{ma} of all the most argillaceous levels, using the corrected values of ϕ_N and of ρ_b. We determine the maximum value $\rho_{ma\,max}$ of this set of values.

The corresponding level is considered to be composed of pure clay if $\rho_{ma\,max}>3.1$ or if the corresponding value of $M<0.60$.

If the value of $\rho_{ma\,max}$ is higher than 2.90, we calculate the clay content V_{Cl} by interpolation and then the clay parameters ϕ_{NCl}, Δt_{Cl}, etc., in each given interval of 250 feet, as described earlier.

Figs. 9 and 10 represent the flow chart of the operations of stage IV.

Block 82 represents the selection of the low-clay levels for which the clay proportions $V_{Cl\,GR}$ and $V_{Cl\,SP}$ computed in phase III_s are lower than 0.2.

Block 83 determines whether a value of R_w appears among the initial data.

If the affirmative, this value R_{wa} is recorded (block 84). If no approximate value is known, one is computed.

We read the value of R_{mf} appearing in the initial data (block 85).

Block 86 represents the computation of the first approximate value R_{w1} from SSP.

Block 87 determines whether we have a measurement of R_{xo}. If we do, we compute a second approximate value R_{w2} from the maximum of the ratio R_{xo}/R_t according to the formula (24) (block 88).

If we have no measurement of R_{xo}, we choose $R_{w2}=R_{w1}$ (block 92).

Finally, we take as an approximate value R_w' the smallest of the values R_{w1} and R_{w2} (block 93).

Block 94 represents the beginning of the computation of the optimization function $F(\phi_N\ R_{t(i)})$.

Block 95 represents the series of values of $d\phi_N$ located on either side of zero.

Block 96 represents the series of values of R_w located on either side of R_w' or R_{wa}, kR_w'.

Block 97 represents the calculation of the function $\phi_N R_{t(i)}=\phi_{N(i)}+d\,\phi_N-\phi R_{t(i)}$ for a level (i) and a pair of values of $d\,\phi_N$ and of kR_w'.

Block 98 compares $\phi_N R_{t(i)}$ with $\phi_{N\,ma1}$ which is known. If $\phi_N R_t<\phi_{N\,ma1}$, $F_{(i)}=-1$ and the partial sum $\Sigma=\Sigma'=1$, Σ' being the preceding value of the partial sum (block 99).

If $\phi_N R_t>\phi_{N\,ma1}$ the block 100 determines whether $\phi_N R_t>\phi_{N\,ma2}$. If such is the case, $F_{(i)}=0$ and $\Sigma=\Sigma'$ (block 101). If not, $F_{(i)}=+1$ and $\Sigma=\Sigma'+1$ (block 102).

The program is pursued by a loop 103. When this loop is completed, we obtain the sum $\sum_i F_{(i)}$ (block 104) corresponding to a pair of values of kR_w' and $d\,\phi_N$.

The program is then pursued by a loop 105 making it possible to process successively all the values of R_w without modifying $d\,\phi_N$. A new loop 106 then makes it possible to process successively all the values of $d\,\phi_N$.

Finally, we record (block 107) the maximum value $\sum_i F_{(i)\,max}$ and the values $d\,\phi_N=A$ and R_{waN} which correspond to this value.

The rest of the program is shown in Fig. 10.

Block 108 determines whether the maximum value of $\sum_i F_{(i)}$ corresponds to an end value of the set of values of R_w or the set of values of $d\,\phi_N$.

If not, block 109 determines whether the maximum value $\sum_i F_{(i)\,max}$ is higher than one and a half times the largest of the values of $\sum_i F_{(i)}$ corresponding to the end values of R_w or of $d\,\phi_N$.

If the reply of block 108 is affirmative or if the reply of block 109 is negative,

there is no sufficiently clear maximum (block 110), In this case, we selected the levels j which correspond to $F_{(j)}=+1$ (block 111).

For this set of points, we study the optimization of the function $\sum_j F''(\rho_b, \phi_N)$ (block 112). This is carried out as in blocks 94—107 (Fig. 9) with $F''=\rho_{ma}\ N_{(j)}$ (Eq. 12).

In the case where a clear maximum of the function $F_{(j)}$ has been found corresponding to the values $d\phi_N=A$ and R_{waN} which are not limit values, we selected the levels j for which $F_{(j)}=+1$ when $d\phi_N=A$ and $kR_w'=R_{waN}$ (block 113).

Block 114 represents the optimization calculations for the function $\sum_j F'(\rho_b, R_t)$. This procedure is carried out in a manner similar to that for obtaining the maximum of the function $F=QR_t$ (Eq. 7 as represented by blocks 94 and 107. The function F' is computed using Eq. 9 as a function of R_w and $d\rho_b$. Values of R_w and $d\rho_b$ are varied and the function $F'_{(j)}$ is assigned a value of +1 or −1 dependent upon the relationship between ρ_{ma} $R_{t(j)}$ and ρ_{ma1} and ρ_{ma2}. For each of the pairs of values, $\sum_j F'_{(j)}$ is the sum for all the levels, j, selected.

Block 115 represents the results of these calculations which lead to a maximum of $\sum_j F'_{(j)}$ for a pair of values $d\rho_b=B$ and R_{waD}.

Block 116 represents the comparison of R_{waN} and R_{waD}. If these values are not very different, for example less than ±15%, it is possible to make a simple calibration of ϕ_N by a scale shift. The multiplying coefficient C=1 (block 117).

If, on the other hand, R_{waN} and R_{waD} are very different, it is necessary to introduce into the calibration of ϕ_N a sensitivity coefficient C which is chosen to vary between 0.7 C_o and 1.4 C_o with $C_o=$

$$C_0=\sqrt[n]{R_{waN}/R_{waD}}$$

Block 119 represents the optimization of the function $\sum_j F''(\rho_b, C.\phi_N)$ whose calculations are identical to those described for the optimization of the function $\sum_j F_{(j)}$. This calculation furnishes the value of the multiplication coefficient C_m.

Block 120 likewise represents the optimization calculations for the function $\sum_j F''(\rho_b, \phi_{No})$ in which ϕ_{No} is given values equal to $C_m(\phi_N+d\phi_N)$ and $d\phi_N$ and $d\rho_b$ are varied.

Finally, we determine the calibration coefficients C_m, $d\phi_{Nm}$ and $d\rho_{bm}$ and the corrected measurements of ϕ_{No} and of ρ_{bo} which are used for the subsequent operations are:

$$\phi_{No}=C_m.(\phi_N+d\ \phi_N)$$

$$\rho_{bo}=\rho_b+d\ \rho_{bm}$$

in which ϕ_N and ρ_b represent the values read on the logs (block 121).

In conclusion, the technique just described provides operations preliminary to the operations described in the French patent mentioned earlier, which make it possible to obtain values of the clay parameters and of the clay content, and to make a first calibration of measuring instruments for porosity ϕ_N and for density ρ_b in formations having a complex lithology.

Of course, similar principles can be applied to other cases such as for example oil or gas bearing shaly sand formations for providing signals representative of input parameters required for evaluating these formations. One technique for such evaluation is described in detail in the above-mentioned French Patent 71.02767 granted May 2, 1973 and published under No. 2,080,945. A technique is described hereinafter to automatically combine signals representative of well logging measurements in shaly sand formations to provide input parameters for the evaluation technique of this French patent and the terminology used in connection with said shaly sand evaluation technique is adhered to.

As explained in the French Patent 71.02767 (published under No. 2,080,945),

various crossplots have been used to provide the input parameters required for the evaluation technique disclosed therein. One of these is a crossplot of the density derived porosity ϕ_D versus the neutron porosity ϕ_N shown in Fig. 12. As shown therein, certain points can readily be placed on the crossplot. It is known that in the water, both the density and neutron derived porosities will be equal to 1. Thus, the water point, W can be placed on a crossplot. It is also known that pure silt, which is primarily quartz, will be at the same point as quartz, designated Q—S, on the crossplot, and dry clay, designated Cl_D will be at the point Cl_D on the crossplot. A triangle can be drawn on the crossplot connecting these three points and in water bearing formations, all plotted ϕ_N, ϕ_D points will fall within this triangle. Furthermore the relative distance of a plotted point from the three apexes of the triangle gives the relative proportions of water, silt and quartz, and dry clay for the formation from which this point is derived.

By plotting a plurality of ϕ_N, ϕ_D points from a formation interval, certain characteristics of the formation can be obtained. For example, assume that a formation interval has produced the plotted points shown in Fig. 12. Those points falling in the area X are known to correspond to shale formations and a line drawn from the origin through the center of gravity of the shale points is designated the shale line. Since it is known that pure shale has generally almost no effective porosity, the shale line corresponds to zero porosity and any point plotted on the shale line can be said to have zero porosity. The intersection of the shale line with the line drawn between the points Cl_D and W, provides the characteristic response for wet clay associated with the shale and is designated Cl_W. Two required input parameters, ϕ_{Nc1} and ϕ_{Dc1}, are defined as the ϕ_N and ϕ_D values respectively of the Cl_W point. The position of this point Cl_W relative to the water and dry clay points gives the amount of water associated with clay W_{c1}.

It is known that clean sand formations affect ϕ_N and ϕ_D equally. Thus, any points falling on or near a line which subtends an angle of 45° and ϕ_N and ϕ_D axis are derived from clean sand formations. This line is designated as the sand line. Points falling in the area Y between the sand and shale lines correspond to shaly sands. These points exhibit a definite trend between the shale and sand line, and a line which best fits these points designated the shaly sand trend line can be drawn between the sand and shale lines. The intersection of this shaly sand trend line with the sand line defines another required input parameter designated $(\phi_z)_{MAX}$, which is the maximum porosity associated with the formation under consideration. The intersection of the shaly sand trend line with shale line gives a point called the hard shale point designated Sh_o. The fact that this trend line points toward a unique point on the shale line indicates that the shale normally associated with the sand has the unique composition as a combination of wet clay and silt represented by the point Sh_o. The neutron and density derived porosity characteristics for the shale designated at the Sh_o point are designated $(\phi_N)Sh_o$ and $(\phi_D)Sh_o$ respectively are two additional required input parameters. Points plotted in the area Z above the clean sand line most likely represent hydrocarbon bearing formations since hydrocarbons and especially gas tend to decrease ϕ_N and increase ϕ_D.

Thus by using a ϕ_N—ϕ_D crossplot a log analyst can select the input parameters $(\phi_z)_{MAX}$, ϕ_{NSh_o}, ϕ_{NC1} and ϕ_{DC1}. In accordance with one feature of the present technique, these parameters are selected automatically.

In addition to the density and neutron derived porosity readings, various indicators influenced by the clay content and hereinafter referred to as shale indicators are utilized in the analysis of shaly sand formations. Two of these shale indicators are the spontaneous potential and gamma ray measurements. As disclosed in the above-mentioned French Patent, these measurements are segregated into groups. Therefore, the evaluation technique disclosed therein requires input parameters which provide discrimination between the groups.

Considering first the spontaneous potential measurements, SP_{SH} is the minimum spontaneous potential measurement associated with shale formations and SP_{SHL} is the SP discriminator indicating an upper limit for the SP measurements in shales. Similarly, SP_{SD} is the highest reliable spontaneous potential measurement associated with sand formations and SP_{SDL} is the SP discriminator indicating a lower limit for spontaneous potential measurements in sand formations. Considering the gamma-ray measurements, GR_{SH} is the maximum gamma-ray measurement associated with shale formations and DAX is the gamma-ray discriminator providing a lower limit for the gamma ray values in shale formations. GR_{SD} is the lowest reliable value of gamma-ray

measurements associated with sand formations and DALIM a gamma-ray discriminator providing an upper limit for gamma-ray measurement in sand formations.

As another feature of this technique, GR_{SH}, GR_{SD}, DAX, DALIM, SP_{SH}, SP_{SD}, SP_{SHL}, and SP_{SDL} are automatically determined. In addition to the input parameters discussed above, other parameters are required. One is the formation water resistivity, R_w at the formation temperature and the formation depth level of interest. Another is REC, the resistivity of clay and another is RESH, the maximum resistivity of shales in the formation which is used as a shale discriminator in the shaly sand analysis described in the referenced French patent. In accordance with this technique, R_w, REC and RESH are automatically determined.

To increase the accuracy of the shaly sand analysis, zero shifts, ZSN and ZSD, may have to be applied to the neutron and density derived porosity measurements, respectively. As still another feature of this technique, ZSN and ZSD are automatically determined.

The analysis of the borehole measurements to automatically select the various parameters useful in the shaly sand interpretation techniques of the above-referenced French patent can be carried out by considering the entire formation interval of interest as a single unit. However, it has been found to be preferable to divide the formation interval into a number of smaller intervals, hereinafter called measurement intervals, and obtain input parameters for each of these intervals. The measurement intervals can be selected from a pre-interpretation of the well logging measurements and other geological data by a log analyst.

The analysis of the data is carried out in four successive sweeps of the data. The first and second sweeps are preliminary sweeps which are run to compute cutoff values useful in the computation of the input parameters. Sweeps three and four are interpretation sweeps during which the final values of the required parameters are computed.

During the first sweep through the data, a caliper discriminator, CAL_{MAX} is defined for each measurement interval in order to determine bad sections of the borehole so that the density and neutron derived porosity measurements obtained from these sections can be rejected during the subsequent sweeps. The caliper discriminator is computed by taking the average and standard deviation of caliper measurements, CAL_{AV} and σ_{CAL} respectively, at each depth level in the measurement interval in accordance with well known mathematical techniques. If the standard deviation is less than two inches, CAL_{MAX} is set equal to $CAL_{AV}+2$, while if the standard deviation is greater than two inches, CAL is set equal to $CAL_{AV}+\sigma_{CAL}$.

A discriminator used to select clean water sands is computed during sweep 1. This discriminator is defined as follows: the apparent water resistivity, R_{wa}, is a combination of the input measurements such that R_{wa} equals the water resistivity, R_w, only in clean water sand formations. In other formations, R_{wa} does not equal R_w. Thus the apparent water resistivity R_{wa} can be used to characterize clean water sand depth levels in the measurement interval. R_{wa} at each depth level can be computed from different combinations of measurements, and in particular in the following ways:

a) from the ϕ_D measurements

$$R_{wa}(\phi_D=1.25\ \phi_D^2\ R_t \quad (51)$$

b) From the ϕ_N measurements

$$R_{wa}(\phi_N=1.25\ \phi_N^2\ R_t \quad (52)$$

c) From the ϕ_S measurements

$$R_{wa}(\phi_S=1.25\ \phi_S^2\ R_t \quad (53)$$

d) From the ratio R_t/R_{xo}

$$R_{wa}\ (R_t/R_{xo})=R_{mf}\ (R_t/R_{xo}) \quad (54)$$

e) From the SP measurements

$$R_{wa(SP)}=R_{mf}\ e[-17.35\ (SP/(460+T)] \quad (55)$$

where: R_{mf} is the mud filtrate resistivity.

The standard deviation of all the R_{wa} measurements, defined as $\Delta(R_{wa})$ can then be computed by the well known mathematical formula:

$$\Delta(R_{wa})=\sqrt{\frac{\Sigma(R_{wa})^2}{N}-\left[\frac{\Sigma R_{wa}}{N}\right]^2} \quad (56)$$

where: ΣR_{wa} equals sum of R_{wa} values computed using equations 51—55. N equals the number of methods used to compute R_{wa}. Thus at each depth level in the formation, the value of $\Delta(R_{wa})$ can be computed. In order to compare the values of $\Delta(R_{wa})$ at different depth levels of the formation, ΔR_{wa}) normalized, called R_{wv} is then found:

$$R_{wv}=\frac{\Delta(R_{wa})}{R_w} \quad (57)$$

where: R_w is the value of water resistivity preselected for the measurement interval from known formation characteristics as is well known in the art.

Theoretically, the value of R_{wv} should equal zero in clean water sand formations since the values of R_{wa} computed using equations 51—55 should be equal in these formations. In shales, shaly sand and hydrocarbon bearing formations, the values of R_{wa} computed using equations 51—55 will differ from each other and R_{wv} will be greater than 0. In practice, it has been found that the value of R_{wv} will not equal zero even in clean water sands due to measurement errors and other perturbing influences. However, R_{wv} is a minimum in clean water sands and a limit value of R_{wv}, called $R_{wv\,MAX}$, can be used as a discriminator for determining clean water sand formations.

As described above, one of the features of the above identified French Patent is the use of certain borehole measurements as shale indicators for the interpretation of shaly sand formations. During sweep 1, each measurement interval is analyzed to determine whether the measurements are good shale indicators within an interval.

To this end, the following clay or shale indicators are considered:

1) Ratio of the density derived porosity to the neutron derived porosity, ϕ_D/ϕ_N;

2) Difference between the neutron derived porosity and the density derived porosity, $\phi_N-\phi_D$;

3) Gamma-ray measurements, GR;

4) Gamma-ray measurements normalized for bulk density, GRN equal to $GR.\rho_b$;

5) Spontaneous potential measurement SP, and

6) A lithology dependent parameter, XM, which is equal to $189-\Delta t/\rho_b-1$. Greater detail as to this parameter can be had by reference to U.S. Patent 3,590,228 issued to Burke on June 29, 1971, and to the pamphlet entitled, "Schlumberger Log Interpretation", Volume 1—Principles, published in 1972).

These shale indicators are correlated for each measurement interval in the same way as described in connection with Stage III_1 of the previously described technique, using the following equation for the correlation function, analogous if not identical to equation 16:

$$R_{xy}=\frac{N\Sigma x_i y_i-\Sigma x_i \Sigma y_i}{\sqrt{\left[N\Sigma x_i^2-(\Sigma x_i)^2\right]\left[N\Sigma y_i^2-(\Sigma y_i)^2\right]}} \quad (58)$$

After all the correlation coefficients have been computed, the highest value of the correlation coefficient is selected to identify the pair of shale indicators providing the best correlation. The correlation of the other pairs of shale indicators is then checked against the correlation of the best pair of shale indicators to determine whether other shale indicators are acceptable and reliable.

Once the correlation coefficients for a measurement interval have been analyzed, new variables can be defined for that interval by combining the availability of the shale indicator and its reliability in the interval. These variables are:

XDN=1 when $\phi_N-\phi_D$ is a good shale indicator;

XSP=1 when SP is available, a good shale indicator and correlates negatively with shale content, i.e., has a negative polarity;

XSP=−1 for reversed SP and SP is available and a good shale indicator, i.e., SP has a positive polarity;

XGR=1 when GR is available and a good shale indicator;

XGR=2 when normalized GR provides a better shale indication than GR;

XDT=1 when Δt is available and XM is a good shale indicator.

When any of the measurements are not good indicators, the value of the associated variable is set equal to 0.

For each measurement interval, sweep one identifies a best shale zone, a zone

being at least four consecutive depth levels said best shale zone corresponding to most argillaceous levels as determined in a manner essentially analogous to those of Stage III_2 of the first previously described technique. The ϕ_D and ϕ_N measurements in that zone are used to compute minimum ϕ_D/ϕ_N, $(\phi_D/\phi_N)_{min}$ and maximum $\phi_N-\phi_D)_{max}$. In addition, if the gamma-ray is a good shale indicator in the interval, the gamma ray measurement in the best shale zone is identified as GR_{Max}. Similarly, if XM is a good shale indicator in the interval, XM in the best shale zone is identified as M_{min}. If the spontaneous potential is a good shale indicator in the interval, a minimum SP, SP_{min} is identified in the best shale zone. However, if the reverse SP is indicated for the interval, then the maximum SP, SP_{max} is identified as the value of the SP in the best shale zone.

The best clean sand zone is also identified as including least argillaceous levels for the interval and the minimum, R_{wv}, the maximum ϕ_D/ϕ_N, the minimum GR, GR_{min}, the maximum XM, M_{max} and maximum or minimum spontaneous potential, SP_{max} or SP_{min} depending on whether the SP is reversed in the measurement interval, are determined from that zone.

In determining the best shale or sand zones the same statistical technique as described earlier in connection with Stage III_2 is used to identify zones for which the indicators are maximum or minimum. The indicators are made comparable by normalizing their variations as previously described for Stage III_2, the statistical maximum and minimum of each of the clay indicators being obtained by using equation (17).

Then, for each zone, i, of the interval, the function $P'_{(i)}=\sum_j F'(i,j).\text{sign}(i,j)$ is computed where $F'(i,j)$ is defined by equation (18) and we choose as the best shale zone and as the best sand zone of each interval those which give the function $P'_{(i)}$ its maximum value under the same conditions as indicated in Stage III_2 for the most and the least argillaceous depth levels.

Once the best shale and sand zones are determined, the following parameters can be determined for the measurement interval:

a) Gamma-Ray for shales, GR_{sh}

$$GR_{sh}=GR_{max} \tag{59}$$

b) Spontaneous potential in shale, SP_{sh}

$$SP_{sh}=SP_{min} \tag{60}$$

For reversed SP

$$SP_{sh}=SP_{max} \tag{60a}$$

c) $$\phi_{NCL}=\frac{(\phi_N-\phi_D)_{max}}{1-(\phi_D/\phi_N)_{min}} \tag{61}$$

d) $$\phi_{DCL}=\phi_{NCL}\left[(\phi_D/\phi_N)_{min}\right] \tag{62}$$

e) $$\phi_{SSH}=1-0.0124\ M_{Min}\ (1-\phi_{DCL}) \tag{63}$$

From the best clean sand zone, the gamma-ray and spontaneous potential in clean sands for the measurement interval, GR_{SD} and SP_{SD} respectively is set equal to GR_{Min} and SP_{Max} respectively. If the interval exhibits a reversed SP, SP_{SD} is set equal to SP_{Min}.

To check the values of GR_{SD} and GR_{SH} computed for each measurement interval the maximum GR_{SH}, called $GR_{SH\ Max}$ and minimum GR_{SD}, called $GR_{SD\ Min}$ computed for all the measurement intervals is selected. Any value of GR_{SD} greater than 1.2 $GR_{SD\ Min}$ and any value of GR_{SH} less than 0.8 $GR_{SH\ Max}$ is rejected. Similarly, the minimum R_{wv}, $R_{wv\ Min}$ for the entire logging interval is selected and a cutoff for clean sands $R_{wv\ Max}$ is computed as $2R_{wv\ Min}$.

It may be found that various parameters cannot be computed for certain measurement intervals. If this occurs the values of the omitted parameters for a particular interval can be inserted once all the measurement intervals have been analyzed according to the following procedure. First, if the parameter is not computed

for the lowest measurement interval, the value of the parameter in the lowest measurement interval is set equal to the value of the parameter at the next higher interval where it has been reliably computed. In any other interval where the parameter has not been computed, it is given the value of the next previous deeper interval where it has been computed. If the parameter has not been computed for any measurement intervals, a preselected value of the parameter can be assigned for all intervals. In the case of parameters relating to gamma-ray, spontaneous potential or sonic measurements, no values are assigned to an interval where the measurement is unreliable as determined by the shale indicator correlation.

Once the sand and shale parameters have been determined for each measurement interval, first approximate values for sand and shale discriminators based on the SP and GR measurements can be computed using the following equations:

II. Gamma-ray

a) Shale discriminator: DAX

$$DAX=GR_{SD}+0.65\,(GR_{SH}-GR_{SD}) \quad (66)$$

b) Sand discriminator: DALIM

$$DALIM=GR_{SD}+0.15\,(GR_{SH}-GR_{SD}) \quad (67)$$

III. Spontaneous Potential

a) Shale discriminator: SP_{SHL}

$$SP_{SHL}=|SP_{SH}+0.2\,(SP_{SD}-SP_{SH})| \quad (68)$$

b) Sand discriminator: SP_{SDL}

$$SP_{SDL}=|SP_{SH}+0.8(SP_{SD}-SP_{SH})| \quad (69)$$

These values of discriminators can be used against GR and SP measurements throughout the interval to select more shaly depth levels on the one hand and cleaner depth levels on the other.

During the second sweep of the data, the default value of clay resistivity REC and maximum resistivity in shales, RESH, are computed. These parameters are computed using a general statistical technique which is also utilized for the computation of other required parameters.

Let us now direct our attention to a general discussion of this statistical technique. The relationship between the value of a particular parameter and the number of times that the value of the parameter occurs within an interval of interest can be determined. This can be visualized by referring to Figure 13. In Fig. 13 a value of I, representing the parameter plotted along the abscissa and the number of times, N, that a particular value of the parameter occurs is plotted along the ordinate. Since the total number of points is also known the value designated I_{Min} can then be ascertained. I_{Min} is the lowest value of I which leaves at least 5% of the total number plotted points below it provided additionally that the number of points at locations below I_{Min} is greater than a predetermined value. Similarly, I_{Max} is the highest value of I which leaves at least 5% of the total number of points above it.

Alternatively, I_{Max} and I_{min} can be found by building a frequency array comprising a plurality of cells with the value of I representing an index value for determining the location of a cell in the array. Preferably, I is scaled to be functionally related to the parameter. Then each time a value of I is computed, the number N in the cell corresponding to I is updated to reflect the total number of times that a particular value of I is computed. After the array is complete, it can be scanned to determine I_{Min} and I_{Max}. Then the value of the parameter corresponding to I_{Min} and I_{Max}, designated X_{Min} and X_{Max} respectively, can be ascertained.

Returning now to the determination of RESH and REC, the value of the formation resistivity, R_t, derived for depth levels which appear to correspond to shale formations is used to compute an index, I, for a frequency array

$$I=20\ Log_{10}\ R_t+15 \quad (70)$$

After all the data in the interval has been analyzed, I_{Max} and I_{Min} are determined and REC and RESH are computed:

$$REC=e\,[0.0115\,(X_{Min}-15)] \quad (71)$$

$$RESH=e\,[0.115\,(X_{Max}-15)] \quad (72)$$

where X_{Min} and X_{Max} correspond to the value of R_t at the cell locations I_{Min} and I_{Max} respectively.

The value of the caliper measurements in shale, CAL_{Sh}, is computed by building a frequency array and computing the index as:

$$I=5\ (CAL-5.7) \tag{73}$$

The minimum value of I, I_{Min} for the array is identified and CAL_{Sh} can then be computed as:

$$CAL_{SH}=0.2\ X_{Min}+5.8 \tag{74}$$

where X_{Min} is the value of CAL for the I_{Min} location in the array.

Using only those depth levels in the measurement interval corresponding to clean formations, as determined by the previously computed discriminators, the parameter ϕ_{Max} is computed by building a frequency array with the index, I computed as

$$I = 100\sqrt{0.5(\phi_D{}^2+\phi_N{}^2)} \tag{75}$$

for $\phi_D > \phi_N$, i.e., points above the clean sand line or,

$$I=100\ \phi_D \tag{76}$$

for $\phi_D \leq \phi_N$, i.e., points below the clean sand line. At the end of the interval, X_{Max} corresponding to I_{Max}, is determined and ϕ_{Max} is computed as:

$$\phi_{Max}=0.01\ X_{Max} \tag{77}$$

Next during sweep 2, the compaction correction for the sonic (CP) and the shifts to be applied to density and neutron porosities (ZSD and ZSN) are computed. A compaction correction factor, CP, for the sonic measurements can be computed for every interval where the sonic measurements are available. For each clean water sand depth level in the measurement interval, a running sum of ϕ_S and ϕ_N, $\Sigma_1\phi_S$ and $\Sigma_1\phi_N$ respectively, is computed. When all depth levels in the interval have been considered, the average of ϕ_S and ϕ_N for the N considered measurement is computed as:

$$\phi_{S\,(AVI)}=\frac{\Sigma_1\,\phi_S}{N} \tag{78}$$

$$\phi_{N(AVI)}=\frac{\Sigma_1\,\phi_N}{N} \tag{79}$$

The compaction correction factor is then:

$$CP=\frac{\phi_{S\ (AVI)}}{\phi_{N\ (AVI)}} \tag{80}$$

When a compensated formation density logging device (FDC) is utilized to obtain measurements of formation bulk density, ρ_b, for computation of the density derived porosity ϕ_D, a correction factor, $\Delta\rho$, is automatically applied to the measured value to compensate for errors introduced by such borehole conditions as mudcake, roughness of the borehole or weight of the drilling mud. The values of $\Delta\rho$ in front of shale formations with smooth holes and average drilling mud weight should average zero. Even in a borehole having adverse conditions, the minimum value of $\Delta\rho$ should be approximately zero. If the $\Delta\rho$ reading is consistently high and is above zero in front of shales, this generally signifies a miscalibration in the FDC tool which must be considered when deriving the input parameters. The departure of $\Delta\rho$ from zero can be expressed as a zero shift of $\Delta\rho$ (ZSDR).

To check the minimum value of $\Delta\rho$ in shale formations, a frequency array is built with index I computed as:

$$I=100\ (\Delta\rho+0.265) \tag{81}$$

for all shale depth levels in a measurement interval. The value of X_{Min} corresponding to I_{Min} is determined for the interval and ZSDR is computed as

$$ZSDR = -0.006\ (X_{Min} - 26) \tag{82}$$

A negative value of ZSDR indicates that the bulk density ρ_b has been over-corrected by $\Delta\rho$ and that the density derived porosity ϕ_D is too low.

To determine the shifts ZSD and ZSN, the average values of ϕ_D, ϕ_N and ϕR_t, (the wet sand porosity derived from the R_t measurement), designated $\phi_{D(AV)}$, $\phi_{N(AV)}$ and $\phi R_{t(AV)}$ respectively for clean water sand levels over the entire logging interval are required. Therefore, at every depth level corresponding to a clean water sand, as determined by the sand discriminators the sums of ϕ_D, ϕ_N, and ϕR_t, designated $\Sigma\phi_D$, $\Sigma\phi_N$, $\Sigma\phi R_t$, respectively, are computed. ϕR_t is computed at each appropriate depth level as:

$$\phi R_t = \sqrt{\frac{0.8\,R_w}{R_t}} \tag{83}$$

where R_w is the input value of R_w for the interval containing the depth level of interest. Then if N is the total number of clean sand levels in the interval:

$$\phi_{D(AV)} = \frac{\Sigma\phi_D}{N} \tag{84}$$

$$\phi_{N(AV)} = \frac{\Sigma\phi_N}{N} \tag{85}$$

$$\phi R_{t(AV)} = \frac{\Sigma\phi R_t}{N} \tag{86}$$

If the bulk density and neutron measurements are well calibrated and the matrix parameters used in computing ϕ_D and ϕ_N correspond to the actual lithology of the formation, then:

$$\phi_{D(AV)} - V_{Cl\ min}\left[\phi_{DCL(AV)}\right] = \phi_{N(AV)} - V_{Cl\ Min}\left[\phi_{NCL(AV)}\right] \tag{87}$$

where: $V_{CL\ Min}$ is the value of clay content of the cleanest sand in the formation previously selected by the log analyst according to geological conditions; $\phi_{NCL(AV)}$ and $\phi_{DCL(AV)}$ are the average ϕ_{NCL} and ϕ_{DCL} over all the measurement intervals, computed from the preliminary values ϕ_{NCL}, ϕ_{DCL} determined during Sweep I.

If the clay content of the cleanest sands is zero then

$$\phi_{D(AV)} = \phi_{N(AV)} \tag{88}$$

A variable $\Delta\phi$ can now be defined as:

$$\Delta\phi = \phi_{D(AV)} - \phi_{N(AV)} - V_{CL\ Min}\left[\phi_{NCL(AV)} - \phi_{DCL(AV)}\right] \tag{89}$$

$\Delta\phi$ provides a measure of how far the average of the ϕ_N and ϕ_D points fall from the clean sand line. Since in clean sands, the average of the ϕ_N and ϕ_D points should fall on or near the clean sand line, the value of $\Delta\phi$ provides a measure of the calibration error of the neutron and density measurements.

To check the calibration error, $\Delta\phi$ is computed using equation (89). If $\Delta\phi$ equals zero, the calibrations are assumed to be correct and ZSD=ZSN=0. If $\Delta\phi$ is greater than zero, indicating that the $\phi_{D(AV)}$, $\phi_{N(AV)}$ point is above the clean sand line, $\Delta\phi$ is recalculated assuming that V_{CLMIN} equals zero. This is equivalent to moving the $\phi_{N(AV)}$, $\phi_{D(AV)}$ point to the right on the ϕ_D—ϕ_N crossplot (Fig. 12) parallel to the shale line. If $\Delta\phi$ is now equal to or less than zero indicating that the $\phi_{N(AV)}$, $\phi_{D(AV)}$ point is on or to the right of the clean sand line, the calibration of the neutron and density

measurement is assumed correct. However, if $\Delta\phi$ is still greater than zero, then it is assumed that either the neutron or density measurement is incorrectly calibrated. The decision on which of the density or neutron is incorrect is made as follows: Prior to the selection of the input parameters, the log analyst may have applied a zero shift to either the neutron or bulk density measurements. If input shifts were applied so as to increase the density derived porosity and decrease the neutron porosity measurement, or if no input zero shift has been applied to either the neutron or density measurement then the bulk density derived porosity ϕ_D is assumed to be in error and the density porosity must be changed by $ZSD=\Delta\phi$. If a negative input zero shift was applied to ϕ_N and no input zero shift was applied to ϕ_D it is assumed that ϕ_N is in error and a zero shift $ZSN=\Delta\phi$ is applied to the neutron derived porosity value of ϕ_N.

When $\Delta\phi$ is less than zero, indicating that the $\phi_{D(AV)}$, $\phi_{N(AV)}$ point falls below the clean sand line, the decision on which of the density or neutron is in error is made by assigning a weight to factors which could have caused a calibration error on each measurement.

The error factors considered in weighting of ϕ_N are: (1) was an input shift applied to ϕ_N; (2) is the neutron measurement of side wall neutron porosity SNP not mudcake corrected; (3) is the minimum CP for all intervals less than 0.9 and (4) is $\phi R_{t(AV)}$ closer to $\phi_{D(AV)}$ than to $\phi_{N(AV)}$. For the ϕ_D measurement the following are considered: (1) whether ZSDR is negative and the weight of the drilling mud is between 9.5 and 12 pounds; (2) whether $\phi R_{t(AV)}$ is closer to $\phi_{N(AV)}$ than $\phi_{D(AV)}$; and (3) whether an input shift was applied to ϕ_D; and (4) whether ϕ_D was computed using a ρ_G (grain density) not equal to 2.65. The weights of the error factors for ϕ_N and ϕ_D are compared and ZSN is set equal to $\Delta\phi$ if the weight for ϕ_N is equal to or greater than the weight for ϕ_D. ZSD is set equal to $-\Delta\phi$ if the weight of errors for ϕ_D exceeds the weight of errors for ϕ_N.

After the zero shift of neutron and density measurements have been determined the computed value of CP can be corrected according to:

$$CP=\frac{\phi_{S(AV)}}{\phi_{N(AV)}+ZSN} \tag{90}$$

After computing parameters for all the measurement intervals, consecutive intervals having similar parameters can be grouped together. This grouping of intervals is desirable because the techniques described in the above-mentioned French Patent require intervals as long as possible.

The following criteria are used to determine if two consecutive intervals are different: (1) the input R_w's are different; or (2) ρ_G's are different; or (3) the values of XDN or XSP or XGR are different; or (4) the slopes of the shale line ϕ_{NCL}/ϕ_{DCL} differ by more than 0.07; or (5) the values of GR_{sh} differ by more than 15%; or (6) the values of ϕ_{Max} differ by more than 15%; or (7) the values of CP differ by more than 10%; or (8) the functions (REC ϕ_{NCL} 1.5) differ by more than 30%.

If these tests are passed, the consecutive intervals are grouped by computing average parameters for a new combined interval. These averages are also weighted to reflect the number of measurements used in each interval to compute the parameter. The parameters of the grouped interval are then compared with the parameters of the next consecutive interval to determine whether the next interval should also be grouped into the previous grouped interval.

Sweep 3 of this program is now executed. First, final values of ϕ_{NCL} and ϕ_{DCL} are computed for all the intervals including the newly grouped intervals. Using only depth levels corresponding to shale formations two frequency arrays are built. One corresponds to a plurality of positions of the shale line and is computed as:

$$I=57.29 \text{ arc tan } (\phi_D/\phi_N) \tag{91}$$

where ϕ_D and ϕ_N are optionally modified by the shift ZSD and ZSN computed in the previous sweep. The other array corresponds to a plurality of positions of the line which passes through the clean water point W and the ϕ_D, ϕ_N point of interest and is computed as:

$$I=100\left[\frac{(1-\phi_N)}{(1-\phi_D)}-0.5\right]+1 \tag{92}$$

At the end of the interval, X_{Min} corresponding to I_{MIN} for each array is determined. For the first array, this corresponds to pivoting the shale line (Fig. 12) counterclockwise from ϕ_D equal to 0 until 5% of the points are below the line. The slope of the line at that position is computed as:

$$SLOPE=\tan(0.01745\ X_{Min}) \quad (93)$$

For the second array, this corresponds to pivoting the line clockwise at the water point until 5% of the points are to the right of the line. A parameter XCL representing this line is computed as:

$$XCL=\frac{100}{X_{Min}+49} \quad (94)$$

The values of ϕ_{NCL}, ϕ_{DCL} can be computed by the intersection of these lines:

$$\phi_{NCL}=\frac{1-XCL}{SLOPE-XCL} \quad (95)$$

$$\phi_{DCL}=SLOPE\cdot\phi_{NCL} \quad (96)$$

The hard shale point ϕ_{NSho} is computed next. This is accomplished by building a frequency array for shale points with the index computed as:

$$I=100\ \phi_{Max}\ \frac{(\phi_N-\phi_D)}{\phi_{Max}-\phi_D} \quad (97)$$

After the array is built for all the shale levels in the measurement interval, X_{Min} is determined. This corresponds to scanning the ϕ_N—ϕ_D crossplot from left to right with a line pivoted at ϕ_{Max} until 5% of the shale points remain to the left of the line. The intersection of this line with the shale line gives the value of ϕ_{NSho} which can be computed as:

$$\phi_{NSho}=\frac{X_{Min}}{100+SLOPE\left(\frac{X_{Min}}{\phi_{Max}}-100\right)} \quad (98)$$

where: SLOPE is the slope of the shale line computed as above.

Also of interest is the computation of the water resistivity R_w by different methods. One such method is to find minimum value of the apparent water resistivity R_{wa} computed in clean sand levels. The value of R_{wa} is preferably computed from three porosity measurements, ϕ_D, ϕ_N and ϕ_S by utilizing three frequency arrays. Thus three indices are computed at each sand depth level:

$$I=20\ \log_{10}(1.25\ \phi_D^2\ R_t\ F)+35 \quad (99)$$

$$I=20\ \log_{10}(1.25\ \phi_N^2\ R_t\ F)+35 \quad (100)$$

$$I=20\ \log_{10}(1.25\ \phi_S^2\ R_t\ F)+35 \quad (101)$$

where: F is a temperature conversion factor.

$$F=\frac{TEMP+7}{82} \quad (102)$$

where: TEMP is the temperature in degrees Fahrenheit at the depth level of interest. At the end of each interval, I_{MIN} and the corresponding X_{Min} for each array can be determined and R_w computed as:

$$R_w=e\ [0.115\ (X_{Min}-35)] \quad (103)$$

for each array to provide $R_w(\phi_D)$, $R_w(\phi_N)$ and $R_w(\phi_S)$, water resistivities computed from the minimum of the apparent water resistivities derived from the density, neutron and sonic measurements respectively.

Although the value of the resistivity of the mud filtrate, R_{mf} is measured from samples and is available as an input to any interpretation program, this program computes a value of R_{mf} from the maximum of the "apparent mud filtrate resistivities" R_{mfa} in clean sands over the entire logging interval. To that end, a frequency array is built with:

$$I=20 \log_{10}(R_{mfa})+30 \quad (104)$$

where R_{mfa} is computed as:

$$R_{mfa}=1.25\ R_{xo}\phi_D^2 F \quad (105)$$

for ϕ_D less than ϕ_N, or

$$R_{mfa}=1.25\ R_{xo}\left[\frac{\phi_N^2+\phi_D^2}{2}\right]F \quad (106)$$

for ϕ_D equal to or greater than ϕ_N where: F is the temperature compensation factor computed using equation (102). After all the sand depth levels over the entire logging interval have been considered, I_{Max} and the corresponding X_{Max} are determined and:

$$R_{mf}=e\ [0.115\ (X_{Max}-30)] \quad (107)$$

This value of R_{mf} may be substituted for the measured R_{mf}.

The values of ϕ_{NSho}, ϕ_{NCL} and ϕ_{DCL} have been computed based on the shaly sand model described in the aforementioned French Patent. If the actual structure of the formation in a measurement interval under investigation departs from that model, errors can arise in the computed values of ϕ_{NSho} and ϕ_{NCL}. In particular it has been found that ϕ_{NCL} is sometimes too low because no pure clay is present in the interval or that ϕ_{NSho} is too large because no hard shale is present in the interval. Therefore, the computed values of ϕ_{NSho}, ϕ_{DCL} and ϕ_{NCL} are checked.

As a first step in detecting and correcting possible errors, the neutron porosity at the dry colloid point, ϕ_{NC} is computed using the clay point ϕ_{NCL}, ϕ_{DCL} and the average grain density of dry colloids $\rho_{DC}=2.84$ as follows:

$$\phi_{NC}=1.0-1.115\ \frac{1-\phi_{NCL}}{1-\phi_{DCL}} \quad (108)$$

It is known that ϕ_{NC} should be approximately equal to 0.20 and that a value of ϕ_{NC} less thon 0.13 is very unlikely. Therefore, if ϕ_{NC} is less than 0.13, it is set equal to 0.13 and ϕ_{NCL} and ϕ_{DCL} are recomputed according to:

$$\phi_{NCL}=\frac{0.22}{1-0.78\ SLOPE} \quad (109)$$

$$\phi_{DCL}=SLOPE\ \phi_{NCL} \quad (110)$$

where: SLOPE has been computed using Equation (93).

Next, the silt index, SI, which is a measure of the relative amount silt and total shale in the formation is checked. The silt index is computed as:

$$SI=\frac{\phi_{NSho}}{\phi_{NCL}} \quad (111)$$

If the silt index is less than 0.5, the value of ϕ_{NC} is recomputed using Equation 108—110 and if ϕ_{NC} less than 0.2, it is set equal to 0.2, ϕ_{NCL} recomputed using the following equations:

$$\phi_{NCL}=\frac{0.29}{1-0.71\ SLOPE} \quad (112)$$

and ϕ_{DCL} is recomputed using Equation (110).

The silt index is now recomputed using Equation (111) and if it is less than 0.3, the value of ϕ_{NSho} is suspected of being in error since ϕ_{NCL} has been set using a reasonable value of ϕ_{NC}.

Since ϕ_{NSho} may be nearly equal to ϕ_{Max} and rarely higher than ϕ_{Max}, a check is made to determine whether ϕ_{NSho} is more than 0.01 greater than ϕ_{Max}. If it is, ϕ_{NSho} is set equal to $\phi_{Max}+0.01$ and the value of SI is computed again using Equation (111).

If SI is still less than 0.3, the value of ϕ_{NCL} is again suspected. It has been found that ϕ_{NC} may in some situations, have a value approximately equal to ϕ_{Max}. Therefore, if ϕ_{Max} is equal to or less than 0.3, ϕ_{NC} is set equal to ϕ_{Max}, otherwise ϕ_{NC} is set equal to 0.3 which is the maximum expected value of ϕ_{NC}. ϕ_{NCL} is then recomputed:

$$\phi_{NCL}=\frac{1-0.9\ (1-\phi_{NC})}{1-0.9\ (1-\phi_{NC})\ SLOPE} \quad (113)$$

and ϕ_{DCL} is recomputed using Eq. 60 where: SLOPE is computed using Eq. (93).

The silt index is now computed once again, and if it is still less than 0.3, ϕ_{NSho} is modified by setting SI equal to 0.3 and ϕ_{NSho} recomputed:

$$\phi_{NSho}=0.7\ \phi_{NCL} \quad (114)$$

In the same manner, ϕ_{Max}, ϕ_{NSho}, ϕ_{NCL} and ϕ_{DCL} are checked and eventually modified for all the new intervals.

Next, Sweep 4 is performed. Using the value ϕ_{Max}, ϕ_{NSho}, ϕ_{NCL} and ϕ_{DCL} obtained in the preceding sweep, values of the effective porosity ϕ_e, the amount of shale V_{sh} and the silt index, SI, for each depth level can be determined using a modified shaly sand model. Referring to Fig. 14, there is shown a portion of the $\phi_D-\phi_N$ crossplot of Fig. 12 which has been divided into 6 areas. The values of ϕ_e, V_{sh} and SI are then computed for each depth level as a function of which area the ϕ_D, ϕ_N point for that depth level falls on the crossplot. If the point is in area 1 above the clean sand line, i.e. ϕ_D is greater than ϕ_N, V_{sh} is set equal to zero, SI is computed using Eq. 111 and

$$\phi_e=\sqrt{0.5\ (\phi_D^2+\phi_N^2)} \quad (115)$$

If the point falls below the shale line, area 2, where ϕ_D is less than $(\phi_{DCL}/\phi_{NCL})\ \phi_N$ then ϕ_e is set equal to zero, V_{sh} is set equal to one and SI is set equal to zero if ϕ_N is greater than ϕ_{NCL}. If ϕ_N is less than ϕ_{NSho}, SI is computed using Eq. 111. If ϕ_N is between ϕ_{NCL} and ϕ_{NSho}, SI is computed as:

$$SI=1-\frac{\phi_N}{\phi_{NCL}} \quad (116)$$

For points to the right of the water-clay line (area 3), ϕ_N is set equal to $1-(1-\phi_D)\frac{1-\phi_{NCL}}{1-\phi_{DCL}}$

and the points are then treated as belonging to area 4. For points in areas 4, 5 and 6, the following relationships apply:

$$\phi_e=\frac{\phi_I\phi_{NCL}-\phi_N\ \phi_{DCL}}{\phi_{NCL}-\phi_{DCL}} \quad (117)$$

$$V_{CL}=\frac{\phi_N-\phi_D}{\phi_{NCL}-\phi_{DCL}} \quad (118)$$

where: V_{CL} is the percent amount of clay in the formation. The computation of V_{sh} and SI in each of the areas 4, 5, and 6 is as follows:

For points in area 4, outside the cubic parabola joining ϕ_{Max} and ϕ_{NC}, i.e. ϕ_e greater than $\phi_{Max}\ [1-V_{CL}^2\ (2-V_{CL})]$, V_{sh} is set equal to V_{CL} and SI is set equal to 0.

For points in area 5, outside the cubic parabola joining ϕ_{Max} and ϕ_{Sho}, i.e. ϕ_e greater than $\phi_{Max}\ [1-V_{Sh}^2\ (2-V_{Sh})]$

where:

$$V_{sh}=V_{CL}\frac{\phi_{NSho}}{\phi_{NCL}}$$

for ϕ_e/ϕ_{Max} less than 0.75

$$V_{sh}=1-0.817\ \phi_e/\phi_{Max} \quad (119)$$

and for ϕ_e/ϕ_{Max} greater than 0.75

$$V_{Sh}=\frac{3}{5}\sqrt{\left(1-\frac{\phi_e}{\phi_{Max}}\right)} \quad (120)$$

Then,

$$SI=1-\frac{V_{CL}}{V_{sh}} \quad (121)$$

Finally for points in area 6, SI is computed using Eq. 111 and

$$V_{sh}=\frac{V_{CL}}{1-SI} \quad (122)$$

The default value of clay resistivity, REC, can now be recomputed. Using the values of V_{sh}, SI and ϕ_e at each depth level identified as shale by the shale discriminator, the clay resistivity is computed:

$$R_{Cl}=\frac{R_w\ R_t\ V_{sh}\ (1-SI)^{1.5}}{R_w-1.25\ \phi_e^2\ R_t/(1-V_{sh})} \quad (123)$$

where: R_w is either a pre-selected value for the interval or the value of R_w computed in sweep 3 from the neutron-derived porosity measurement using Eq. 103. The sum of the clay resistivities, ΣR_{Cl}, is accumulated for N depth levels in the interval and REC is computed as the average clay resistivity over the interval:

$$REC=\frac{\Sigma R_{Cl}}{N} \quad (124)$$

A statistical approach can now also be used to compute GR_{SD} and GR_{SH}. For depth levels corresponding to shales, the sum of the gamma-ray measurements, ΣGR_{Sh} and the volume of shale, ΣVG_{Sh} are accumulated. Similarly, for clean sand depth levels the sum of the gamma-ray measurements, ΣGR_{SD} and the volume of shale ΣVG_{SD} are also accumulated. For each interval the average gamma-ray measurement and amount of shale for the shale zones, G_{SH} and VG_{SH}, respectively, and the average gamma-ray measurement and amount of shale for the sand zones, G_{SD} and VG_{SD}, respectively are computed.

The gamma-ray in sand, GR_{SD}, and gamma-ray in shale, GR_{SH} are then computed as:

$$GR_{SD}=G_{SD}-VG_{SD}\frac{G_{SH}-G_{SD}}{VG_{SH}-VG_{SD}} \quad (125)$$

$$GR_{SH}=GR_{SD}+\frac{G_{SH}-G_{SD}}{VG_{SH}-VG_{SD}} \quad (126)$$

The gamma-ray discriminators, DAX and DALIM can now be re-calculated using equations 66 and 67.

A similar approach is used to compute the limits of the SP measurements, SP_{SD} and SP_{SH}. With S_{SD} and VS_{SH} representing the average spontaneous potential and amount of shale of sand levels over the interval, SP_{SD} is computed as:

$$SP_{SD}=\frac{S_{SD}}{1-VS_{SD}} \quad (127)$$

With S_{Sh} and VS_{Sh} representing the average spontaneous potential and amount of shale for shale levels over the interval, SP_{Sh} is computed as:

$$SP_{Sh}=\frac{SP_{Sd}\ (1-V\ S_{Sh})-S_{Sh}}{VS_{Sh}} \quad (127a)$$

The resistivity of water, R_w, can now be computed using the SP_{Sd} measurements. Either a pre-selected value of mud filtrate resistivity, R_{mf}, or the value of R_{mf} computed using Eq. 107 can be used. For a known value of resistivity of mud filtrate, the concentration of NaCl in the mud filtrate in parts per million times 10^6, PPM_{mf}, can be computed:

For R_{mf} greater than 0.3,

$$PPM_{mf}=e^{\left[-5.181-1.066\ \log e\ (R_{mf})\right]} \quad (128)$$

and for R_{mf} less than 0.3

$$PPM_{mf}=e^{\left[92.067+\frac{7969}{\log e\ (R_{mf})-81.833}\right]} \quad (129)$$

From the concentration of NaCl in the mud filtrate, the NaCl concentration in the formation water PPM_w can be computed as:

$$PPM_w=\frac{GRL_w}{1000+0.63\ GRL_w} \quad (129a)$$

where: GRL_w is the concentration of NaCl in water in grams per liter computed as:

$$GRL_w=e^{\left[-31.129+\frac{2.3026}{\frac{1}{13.519+0.4343\ \log_e (GRL_{mf})}-\frac{0.0434\ SP_{Sd}}{460+T}}\right]} \quad (130)$$

and GRL_{mf} is the NaCl concentration of mud filtrate and grams per liter computed from PPM_{mf} as:

$$GRL_{mf}=\frac{1000\ PPM_{mf}}{1-0.63\ PPM_{mf}} \quad (131)$$

Finally, if PPM_w is less than 0.2, R_w is computed as:

$$R_w = e^{\left[\frac{-\log e\ (PPM_w) + 5.181}{1.066}\right]} \quad (132)$$

and if PPM_w is greater than or equal to 0.2, R_w is computed:

$$R_w = e^{\left[81.933 + \frac{7969}{\log e\ (PPM_w) - 92.067}\right]} \quad (133)$$

The value of water resistivity can also be computed for each interval using the ratio of R_{xo}/R_t and the value of R_{mf} either pre-selected or previously computed. To this end, a frequency array can be constructed with:

$$I = 20\ \log_{10}\left(\frac{R_{mf}}{R_{XO}/R_t}\right) + 35 \quad (134)$$

At the end of an interval X_{Min} corresponding to I_{Min} is determined and R_w is computed as:

$$R_w = e\ [0.115\ (X_{Min} - 35)] \quad (135)$$

Once all of the parameters of interest have been computed they can be printed out. Also, punched cards providing the input parameters for the shaly sand interpretation can be automatically prepared as is well known in the art.

Turning now to Figs. 15—26 there are shown computer flow diagrams for carrying out the invention. Although the invention could also be carried out with an analog device or special purpose computer, it is particularly advantageous to use a general purpose computer programmed according to the principles shown and discussed in detail herein.

The program takes four sweeps of the data. Referring first to Fig. 15, there is shown sweep 1. Sweep 1 is entered, block 40' and the input parameters, R_{mf}, R_w, ρ_s and V_{olMin} for the first preselected measurement interval are read, block 42'. One level of logging data from the measurement interval is next read, block 44'. The logging parameters, ϕ_S, ϕ_D, ϕ_N are computed using well known techniques, block 46'. An input zero shift may be also applied to ϕ_D and ϕ_N at this time.

Next, as represented by block 48', a running sum and sum squared for all caliper measurements in the measurement interval is computed. Next, decision element 50' determines whether ϕ_N, ϕ_S or ϕ_D are changing too rapidly by applying fast-break discriminators to these parameters.

Fast-break discriminators are used throughout the program to detect rapid changes in data over small depth changes. Data obtained from these depth levels can be unreliable and therefore is eliminated from consideration. As an example, the fast-break discriminator investigates the following two conditions for the porosity measurements:

ϕ(at depth level) $-\phi$ (previous depth level) $>$ 2 porosity units and

ϕ(at depth level) $-\phi$ (at depth level below) $>$ 3 porosity units
(previous depth level)

If the magnitude of ϕ at the depth level of interest exceeds the value of ϕ at the next lowest depth level by more than two units and it exceeds the value of ϕ at the depth level next below the previous depth level by more than three units, the parameter is considered to be changing too rapidly and the data at the depth level of interest is disregarded.

In addition, decision element 50' asks whether ϕ_D is less than -0.02 or greater than 0.45 or whether ϕ_N is less than 0.1 or whether ϕ_D is greater than $(\phi_N + 0.03)$. If the answer is NO, the program proceeds to decision element 52' which determines whether the ratio ϕ_D/ϕ_N is less than 0.7. If the answer is NO, this indicates that the data is derived from a clean sand formation and R_{wv} is computed for the depth level using equations 51—57, (block 54'). If the answer from decision element 52' is YES,

R_{wv} is set equal to a predetermined value, for example, 10, block 56′, and block 54′ is bypassed. Next, as represented by block 58′, running sums required for the correlation of the shale indicators are computed. As shown, if the answer from decision element 50′ is YES, R_{wv} is set to 10, block 60′, and blocks 52′, 54′, 56′ and 58′ are bypassed.

Next decision element 61′ asks whether the depth level presently being considered is the last depth level in the measurement interval. If it is not, NO answer, the depth level is incremented, block 62′ and the program returns to block 44′ for analysis of the next depth level. After all the depth levels in the measurement interval have been considered, YES answer from decision element 61′, the shale indicators for the measurement interval are correlated using subroutine COMCOR as represented by block 64′.

Referring now to Fig. 16, subroutine COMCOR is shown in detail. COMCOR is entered, block 70′ and each correlation factor, having the general expression R(x, y) is computed using equation 58 as represented by block 72′. Next, the maximum correlation factor for non-identical pairs of shale indicators called CORMAX, is selected, block 74′. The X and Y coordinates of CORMAX are then set equal to M and N respectively, blocks 76′. The variables XDN, XGR, XSP and XDT are initially set to zero, block 78′, after which decision element 80′ determines whether CORMAX is equal to zero.

IF CORMAX is not equal to zero, NO answer from decision element 80′, the program proceeds to determine which shale indicators are reliable for the interval. To this end, decision element 82′ asks whether (M—4) is greater than zero. If the answer is YES, then M is either equal to 5 or 6 indicating that either the SP or XM is a reliable shale indicator. Next decision element 84′ asks whether M equals 6 and if the answer is YES, XDT is set equal to one, block 86′, indicating that Δt is available and that XM is a good shale indicator.

If the answer from decision element 84′ is NO, decision element 88′ determines whether N equals 1 and whether the correlation factor R(5, 1) is greater than zero, i.e. is there positive correlation between the SP and ϕ_N/ϕ_D shale indicators. If the answer is YES, XSP is set equal to one, block 90′. If the answer is NO, decision element 92′ next asks whether N is greater than 1 and whether the correlation factor R(5, N) i.e. the correlation between the SP and either $(\phi_N-\phi_D)$ GR or GRN is negative. If the answer is YES, XSP is set equal to one block 90′. If the answer is NO, XSP is set equal to minus one, block 94′ to indicate that a reversed SP condition exists in the measurement interval.

Decision element 96′ which is entered next either via block 86′, 90′ or 94′ asks whether the absolute value of CORMAX is less than 0.5. If the answer is NO, i.e. CORMAX is greater than 0.5, the program proceeds to determine which other shale indicators when correlated with the shale indicator having the coordinate M is greater than 0.5. Thus if the absolute value of either R(M, 1) or R(M, 2) is greater than 0.5, decision element 98′, XDN is set equal to one, block 100 indicating that $(\phi_N-\phi_D)$ is a good shale indicator. Similarly if the absolute value of R(M, 3) is greater than 0.5, which is asked by decision element 102′, XGR is set equal to one, block 104′ indicating that GR is available and a good shale indicator. If R(M, 4) is greater than R(M, 3) and the absolute value of R(M, 4) is greater than 0.5, decision element 106′, XGR is set equal to two, block 108′ indicating that the normalized gamma-ray is available and a better shale indicator than the gamma-ray measurement itself.

Now the program proceeds to determine whether the absolute value of R(6, 5) the correlation coefficient for SP and XM is greater than 0.5. This is the function of decision 110′. If the answer is YES, decision element 112′ asks whether M equals six. If the answer is NO, XDT is set equal to one, block 114′. If M equals six, YES answer from decision element 112′, decision element 116′ determines whether R(6, 5) is less than zero. If it is, XSP is set equal to minus one, block 118′. If R(6, 5) is not less than zero, XSP is set equal to one, block 120′.

The program proceeds either from blocks 114′, 118′ or 120′ or NO answer from decision element 110′ to decision element 122′ which asks whether XGR is greater than zero or XSP does not equal zero. If the answer is NO, decision element 124′ asks whether the correlation coefficient for GR and $(\phi_N-\phi_D)$, R(3, 2) is greater than the correlation coefficient for SP and $(\phi_N-\phi_D)$, R(5, 2). If the answer is YES, XGR is set equal to one, block 126′, and if the answer is NO, XSP is set equal to one, block 128′. The subroutine returns, block 130′ via either blocks 126′, 128′ or YES answer from decision element 122′.

Returning now to decision element 96′, if the absolute value of CORMAX is less than 0.5, YES answer, decision element 132 asks whether (N—3) is greater than 0.

If N is greater than 3, YES answer, decision element 134′ asks whether N=4 and if the answer is YES, XGR is set equal to two, block 136′. If the answer from decision element 134′ is NO, decision element 138′ asks whether CORMAX is less than zero and if it is, YES answer, XSP is set equal to minus one, block 140′ while if the answer is NO, XSP is set equal to one, block 142′.

Returning to decision element 132′, if the answer is NO, decision element 144′ asks whether N equals three. If N equals three, XGR is set equal to one, block 146′, and if not, XDN is set equal to one, block 148′. The program then proceeds to decision element 122′, via either blocks 140′, 142′, 136′, 146′ or 148′ and then returns via 124′, 126′ or 128′ and 130′ is discussed above.

Returning now to decision element 82′, if M—4 is not greater than zero, NO answer, decision element 150′ asks whether M equals four. If the answer is YES, XGR is set equal to two, block 152′. Otherwise XGR is set equal to one, block 154′. In either event, XDN is next set equal to one, block 156′ after which decision element 160′ asks whether the absolute value of CORMAX is less than 0.5. If the answer is YES, the subroutine returns via 122′, 124′, 126′, 128′ and 130′.

If the answer from decision element 160′ is NO, the program proceeds to decision element 162′ which asks whether the absolute value of either R(5, 3) or R(5, 4) is greater than 0.45. If the answer is YES, decision element 164′ asks whether R(5, 3) is less than zero. If the answer is YES, XSP is set equal to minus one, block 166′ otherwise XSP is set equal to one, block 168′. The program proceeds via either No answer from decision element 162′, or blocks 166′ or 168′ to decision element 170′ which asks whether R(6, 3) or R(6, 4) is less than −0.5. If the answer is YES, XDT is set equal to one, block 172′. In either case, the subroutine returns via 122′, 124′, 126′ or 128′ and 130′.

Finally, if CORMAX=0, YES answer from decision element 80′, XDN is set equal to one, block 174′ and if either the SP, GR, or Δt measurement is available, which questions are asked by decision elements 176′, 178′ and 180′ respectively, XSP, XGR or XDT is set equal to one as represented by blocks 182′, 184′ and 186′ respectively, and the subroutine returns via 122′, 124′, 126′, 128′ and 130′.

After the shale indicators for the interval have been correlated and the determination made as to which shale indicators are available and reliable the program returns to block 190′ (Fig. 15A). As represented by block 190′, the best shale and sand zones for the interval are determined using subroutine MINXN. $(\phi_D/\phi_N)_{Min}$, GR_{Max}, M_{Min} and SP_{Min} or SP_{Max} are identified as the parameters in the best shale zone, and $(R_{wv})_{Min}$, $(\phi_D/\phi_N)_{Max}$, GR_{Min}, M_{Max} and SP_{Max} or SP_{Min} for the best sand zone. Referring to Fig. 17, this subroutine is shown in greater detail.

Referring now to Fig. 17, subroutine MINXN is entered via block 820.

The best shale and sand zones are selected as those zones which correspond to the zones i_1 and i_2 for which the function $P'_{(I)}=\Sigma F'_{(I,J)}\,sign_{(I,J)}$ has a maximum value. The value of sign (i,j) is set equal to or opposite that of the difference (xk_i-xk_j) depending on whether the best shale or sand zones, respectively is sought.

The first zone is considered by setting i and j equal to 1, block 822 and 824 respectively. Then the normalized variation of the difference $(xk_{(I)}-xk_{(J)})$, which is the difference between the values of a shale indicator k for the zones i and j are computed. As represented by block 826, the normalized variation

$$\frac{Dk_{(I,J)}}{Nk}=\frac{xk_{(I)}-xk_{(J)}}{Nk}$$

is computed. Next, decision element 828 asks whether the normalized variation is less than zero. If the answer is YES, the absolute value of

$$\frac{Dk}{Nk}$$

is computed, block 830 and a counter $SM_{(I,J)}$ is incremented, block 832, as explained in greater detail below. If the answer is NO, the absolute value of

$$\frac{Dk}{Nk}$$

is computed, block 834.

As represented by block 836, a partial sum,

$$\sum_k \frac{|Dk|}{Nk} = \Sigma' + \frac{|Dk|}{Nk}$$

is computed, where Σ' is the sum of the preceding k values. Next decision element 838 asks if all clay indicators have been considered and if not, the program proceeds to the next clay indicator, block 840 and returns to block 826. After all the clay indicators k have been considered, block 836 represents the sum, Σ

$$\left|\frac{Dk}{Nk}\right|$$

corresponding to the two zones i and j for all clay indicators. The function

$$F'(i,j) = \frac{1}{1+\alpha \sum_k \left|\frac{Dk}{NK}\right|^n} \qquad (18')$$

can now be computed by choosing for α a positive values, for example 0.12 and for n, a positive value, for example 1. This is represented by block 842. It is seen that Equation 18' is Equation 18 in rewritten form.

Next the function

$$P_{(i)} = \sum_j F'_{(i,j)} \cdot \text{sign } (i,j)$$

is computed. First, as represented by decision element, 844, it is determined whether $SM_{(i,j)}$ is equal to zero, to one or higher than one. If $SM_{(i,j)}$ equals zero that is for every k,

$$\frac{Dk}{Nk} > 0$$

sign (i,j) is set equal to one, block 846. If $SM_{(i,j)}$ equals one that is, if there is one indicator k and only one for this $Dk/Nk<0$, sign (i,j) and if $SM_{(i,j)}$ is greater than zero, $\text{sign}_{(i,j)}$ is set equal to minus 1, block 850. In the case where the best sand zone is sought, we replace Nk by $-Nk$ and we record, in the same manner, $Dk/-Nk<0$, and the sign of (i,j) is determined in the same manner. Knowing the value of sign (i,j) and of the function:

$$F'(i,j) = \frac{1}{1+\alpha \sum_k \left|\frac{Dk}{NK}\right|^n} \qquad (18')$$

the product $F'_{(i,j)}$ sin (i,j) is computed and a partial sum:

$$\Sigma = \Sigma' + F'_{(i,j)} \cdot \text{sign } (i,j)$$

is computed as represented by block 852, Σ' being the preceding value.

Next decision element 854 asks if j is greater than N, where N is the number of zones in the interval. If the answer is NO, j is incremented, block 856 and the program returns to block 824. When all the zones j have been taken into account, the sum from block 852 represents: $P'_{(i)} = \sum_j F'_{(i,j)} \cdot \text{sign } (i,j)$.

After all zones j have been considered with one zone i, decision element 858 asks if i=N. If the answer is NO, i is incremented, block 860 and the program returns to block 822.

After all zones, i, have been considered the program selects the highest value of

$P'_{(1)}$ as represented by block 862 and the zone which corresponds to the maximum of $P'_{(1)}$ is the best shale zone or best sand zone in the interval as represented by block 864.

Next, the shale and sand parameters for the intervals corresponding to the maximum $P'_{(1)}$ are set, block 866. Thus the values of ϕ_D, ϕ_N, GR and SP are determined from the best shale zone and R_{wv}, ϕ_D, ϕ_N, GR and SP are determined from the best sand zone after which the program returns to block 868.

Once the best shale and sand zones for the interval are determined, the program returns to decision element 200′ (Fig. 15A) which asks whether XGR is equal to zero. If the answer is NO, GR_{SH} is set equal to GR_{MAX} and GR_{SD} is set equal to GR_{MIN}, block 202′. If XGR equals zero, block 202′ is bypassed. Next, decision 204′ asks whether XSP equals zero. If the answer is NO, decision element 206′ asks whether XSP is greater than zero. If the answer is YES, SP_{SH} is set equal to SP_{MIN} and SP_{SD} is set equal to SP_{MAX}, block 208′. If XSP is less than zero, SP_{SH} is set equal to SP_{MAX} and SP_{SD} is set equal to SP_{MIN}, block 210′ since a reversed-SP is indicated for the interval. If XSP equals, zero, YES answer from decision element 204′, blocks 206′, 208′ and 210′ are bypassed.

Next, as represented by block 212′, ϕ_{NCL} and ϕ_{DCL} are computed using equations 61 and 62 using $(\phi_N-\phi_D)_{MAX}$ and $(\phi_D/\phi_N)_{MIN}$ computed by subroutine MINXN. Then decision element 214′ asks whether XDT equals zero and it it does not, NO answer, ϕ_{SSH} is computed using equation 63 (block 216′) with M_{MIN} computed by subroutine MINXN. If the answer from decision element 214′ is YES, block 216′ is bypassed.

Next, as represented by block 218′, the average and standard deviation of the caliper measurements designated CAL_{av} and σ_{cal} respectively, for the interval are computed using standard mathematical techniques. If the standard deviation of the caliper measurements is less than two, which question is asked by decision element 220′, the caliper discriminator, CAL_{max} is set equal to $CAL_{av}+2$, as represented by block 222′. If the answer from decision element 220′ is NO, CAL_{MAX} is set equal to $CAL_{av}+\sigma_{cal}$, block 224′.

Decision element 226′ next asks whether the measurement interval just considered is the last one in the logging interval. If it is not, NO answer, the program goes to the next measurement interval, block 228′ and the analysis begins again with block 42′. The program continues until all measurement intervals are analyzed in the above manner at which time the answer from decision element 226′ is YES.

After all the measurement intervals in the logging interval are analyzed, the minimum value of GR_{SD} called $GRSD_{MIN}$ and the maximum value of GR_{SH}, called $GRSH_{MAX}$ for all intervals is selected to provide a check that the value of GR_{SD} and GR_{SH} for each interval correspond respectively to clean sand or shale or shale formations. Similarly, the minimum R_{wv} called R_{wvmin} is selected for use in computing a cutoff for R_{wv} in clean sands. These operations are represented by block 228′. Next, as represented by block 230′, the R_{wv} cutoff for clean sands, called R_{wvmax} is set equal to 2 R_{wvmin} and values of GR_{SD} greater than 1.2 GR_{MIN} and values of GR_{SH} less than 0.8 GR_{MAX} in any measurement interval are eliminated (block 232′).

As represented by block 234′, the gamma ray parameters are now set for those measurement intervals where they are not present, either because they could not reliably be computed in an interval (XGR equal to zero) or because they were eliminated as above (block 232′). This substitution is accomplished by using subroutine FILLAR, shown in detail in Fig. 18.

Referring now to Fig. 18, subroutine FILLAR is entered via block 240′. Next, block 242′ asks whether the parameter to be set is either the sonic, SP, or GR. Since the gamma-ray is to be set, the answer is YES and the program proceeds to decision element 244′ which determines whether the parameter of interest, i.e. gamma ray, has been reliably computed in any interval. If the answer is NO, the value of a parameter is set to a pre-selected value in those intervals where the shale indicator correlation indicates that the parameter is reliable (XGR not equal to zero), block 246′ and then returns, block 248′. If the answer from decision element 244′ is YES, then the value of the parameter in each acceptable interval is set equal to the reliable value of the parameter computed for the next deeper interval, (block 250′) and the program returns, block 248′.

To complete the explanation of the operation of subroutine FILLAR, return now to decision element 242′. If a parameter other than the sonic, SP or GR is to be set, NO answer, the program proceeds to decision element 252′ which asks whether a value for the parameter has been computed for the deepest interval. If the answer is YES, the value of the parameter for each interval where it is not computed is set equal to the value of the parameter at the nearest deeper interval, block 254′ and the program

returns block 248'. If the answer from decision element 252' is NO, decision element 256' asks whether the parameter has been computed for any interval and if it hasn't, NO answer, the parameter for each measurement interval is set to a preselected value, block 258' and the program returns to block 248'. If the answer from decision element 256' is YES, the value of the parameter for the deepest measurement interval is set equal to the value of the parameter computed at the next shallower interval, block 260' and then the values of the parameter for the remaining intervals are set equal to the value computed for the next deeper interval, block 254', after which the program returns, block 248'.

Once the value GR_{SD} and GR_{SH} have been established for each interval by subroutine FILLAR, the program returns to block 270' (Fig. 15B). The value of the GR discriminator in shale, DAX, and the GR discriminator in sands, DALIM, is now computed for each interval using equations 66 and 67, respectively.

Referring now to Fig. 19, there is shown sweep 2. Sweep 2 is entered via block 300. The parameters computed by sweep 1 from the first interval are read, block 302 and the SP shale discriminator, SP_{SHL} and the SP sand discriminator, SP_{SDL} are computed using equations 68 and 69, respectively, block 304. Next, one level of logging data is read, block 306.

Decision element 308 next determines whether the depth level under consideration is in a shale or sand formation. To this end, fast-break discriminators are applied to ϕ_N and ϕ_D and then it is determined whether XGR is greater than zero and GR greater than DALIM; or XSP not equal to zero SP less than SP_{SDL}; or ϕ_D/ϕ_N is less than 0.5; or ϕ_N is greater than 0.45 or less than 0.05; or CAL greater than CAL_{MAX} or ϕ_D less than 0.5. If the answer NO this indicates that a sand formation is present and the data from this depth level is used in the computation of ϕ_{MAX}. To this end, as represented by block 310, a 45 cell array for computing ϕ_{MAX} is entered with an index dependent on the ϕ_D and ϕ_N measurements for the depth level under consideration. Next, decision element 312 asks whether R_{wv} for the depth level under consideration is greater than R_{wvMAX} or whether XGR is greater than zero and GR for the depth level is greater than 1.2 GR_{MIN}. If the answer NO, the value of ϕ_D, ϕ_N and ϕ_{Rt} (computed using Eq. 83) are used for computing a running total of these values for the entire log, block 314. Next, as represented by decision element 316, a fast-break discriminator is applied to ϕ_S and if ϕ_S is not changing too rapidly, NO answer, the values of ϕ_N and ϕ_S for that depth level are used in computing a running sum of the ϕ_N and ϕ_S measurements for one interval, block 318. Via either block 318 or YES answer from decision elements 312 or 316, the program proceeds to decision 320 which determines whether this is the last depth interval. If it is not, NO answer, the depth level is incremented, block 322 and the program returns to block 306 for the analysis of the next depth level.

Returning now to decision 308, if the answer is YES, indicating that a shale formation may be present at the particular depth level, parameters M_1 and N_1 are computed as:

$$M_1 = \frac{0.01\ (1-\phi_S)\ (189-\Delta t_{ma})}{(1-\phi_D)\ (\rho_g - 1)} \qquad (144)$$

$$N_1 = \frac{(1.03-\phi_N)}{(1-\phi_D)\ (\rho_g - 1)} \qquad (145)$$

where: Δt_{ma} is the matrix transit time in $\mu s/ft$ and ρ_g is the grain density block 324. Next decision element 326 asks whether M_1 is less than $(0.55+0.35\ N_1)$ or whether ϕ_D/ϕ_N is greater than 0.75 or whether XGR is greater than zero and GR is less than DAX. If the answer is YES, the program proceeds to the analysis of the next depth level via 320 and 322. If the answer is NO, indicating that a true shale level is present, a 50 cell array for computation for CAL_{SH} is entered with an index value dependent on the value CAL for the depth level under investigation, block 328. Similarly, as represented by block 330, a 50 cell array for computation of $\Delta\rho$ for the entire log is entered with an index dependent upon the value of $\Delta\rho$.

Next, decision 332 asks whether R_t is less than 0.05 or whether ϕ_N is less than 0.05 or whether ϕ_D is less than -0.01. If the answer YES, the program proceeds to the next depth level via 320 and 322. If the answer is NO, a 50 cell array for computing REC and RESH, is entered, block 334 with an index value dependent on the value

of R_t. The program then returns to block 320 and 322 and continues until all the depth levels in the measurement interval have been considered at which time the answer from decision element 320 is YES and the program proceeds to block 336.

As represented by block 336, the CAL_{SH} and REC arrays are now scanned to determine I_{MIN} and the corresponding X_{MIN}. As described above, I_{MIN} is the index of the cell array which leaves at least 5% of the total number of points in the array below that cell number that the number of points at the location of the cell is greater than a predetermined value. Similarly, the ϕ_{MAX} and RESH arrays are scanned to determine I_{MAX} which is the index of the cell which leaves 5% of the total points in the cell above it and the corresponding X_{MAX}. Values of CAL_{SH}, ϕ_{MAX}, RESH and REC are then computed using equations 74, 77, 72 and 71, respectively, block 338. Decision element 340 next asks if RESH is less than 2REC and if it is RESH is set equal to 2 REC, block 342. The value of the compaction correction factor CP is computed next using equation 80, block 344. This completes the analysis for one measurement interval and decision element 346 asks whether this is the last interval to be considered. If it is not, NO answer, the interval is incremented, block 348 and the program returns to block 302 for analysis of the remaining intervals.

After the last interval is analyzed, YES answer from decision element 346, the average ϕ_D, ϕ_N and ϕ_{RT} are computed for the entire log from the running sums of these values, block 349. Next, as represented by block 350, the $\Delta\rho$ array is scanned to determine X_{MIN} and the zero shift in $\Delta\rho$, ZSDR is computed using equation 82. Calibration shifts of ϕ_N and ϕ_D are now computed as represented by block 352. This is accomplished by use of subroutine CALIBR which is shown in greater detail in Fig. 20.

Referring now to Fig. 20, subroutines CALIBR is entered via block 360. Next, decision element 362 asks whether the input value of V_{CLMIN} equal zero, $V_{CL\,MIN}$ being an input parameter. If the answer is NO, ϕ_{NCL} (AV) and ϕ_{DCL} (AV) for the entire log is computed, block 364. If V_{CLMIN} equal zero, block 364 is bypassed. Next, the parameter $\Delta\phi$ is computed using equation 89, block 366 after which decision element 368 determines whether $\Delta\phi$ is equal to, greater than or less than zero. If $\Delta\phi$ equals zero, the program returns via block 370.

If $\Delta\phi$ is positive, decision element 372 next asks if $\Delta\phi$ is greater than 0.05. Since it has been found that a value of 0.05 is the practical maximum value for $\Delta\phi$, if the answer is YES, $\Delta\phi$ is set equal to 0.05, block 374. As represented by block 376, a weight for the ϕ_N measurements, called KN, is incremented by the number of intervals for which a zero shift has been applied to ϕ_N. A weight for the ϕ_D measurements, called KD, is incremented for each interval that either a zero shift has been applied to ϕ_D or where ρ_g is larger than 2.65, block 378. These weights, KN and KD are compared by decision element 380 and if KD is equal to or greater than KN, a zero shift is to be applied to ϕ_D, designated ZSD, equal to $-\Delta\phi$, block 382. Otherwise, the zero shift is to be applied to ϕ_N, called ZSN, equal to $\Delta\phi$ block 384, and the program returns via block 370.

Returning to decision element 368, if $\Delta\phi$ is negative, decision element 386 asks whether $\Delta\phi$ is less than -0.05 and if the answer is YES, $\Delta\phi$ is set equal to 0.05, block 388 for the reasons discussed above. A weighting procedure similar to that discussed above, now takes place. Thus KN is set equal to 2 if the neutron measurement is an SNP but has not been mudcake corrected, block 390. KN is incremented by one if the minimum CP for the entire log is less than 0.9, block 392 and KN is incremented by the number of intervals for which an input zero shift is applied to ϕ_N, block 394. As represented by block 396, KD is set equal to one if the weight of the mud filtrate is between 9.5 and 12 pounds and ZSDR is negative. Decision element 398 next determines if ϕR_t(AV), is closer to ϕ_N(AV) or to ϕ_D(AV). If it is closer to ϕ_D(AV), YES answer KN is incremented by one, block 400 and if it is closer to ϕ_N(AV), NO answer, KD is incremented by one, block 402. Next, KD is incremented by the number of intervals for which either an input zero shift was applied to ϕ_D or for the intervals where ρ_g was greater than 2.65, block 404. Decision element 406 next determines whether KN is equal to or greater than KD. If KN is greater than KD, YES answer, ZSN is set equal to $\Delta\phi$, block 408 and if the answer NO, ZSD is set equal to $-\Delta\phi$, block 410 after which the program returns via 370.

Once ZSN and ZSD have been determined, the next step is to correct CP for neutron shift for each interval using equation 90, block 420′ (Fig. 19B). Next consecutive intervals having similar parameters can be grouped, block 422′. This is accomplished using subroutine MERGIN which is shown in greater detail in Fig. 21.

Referring now to Fig. 21, there is shown in detail the subroutine MERGIN. The subroutine is entered via block 430 and weighted averages of GR_{SH}, ϕ_{MAX}, REC, CP,

ϕ_{NCL}/ϕ_{DCL} and the average value of SP_{SH} for the lowest interval are computed, block 432. The interval is then incremented, block 434 and the parameters of two consecutive intervals are compared. Thus decision element 436 asks whether ρ_{fl}, R_w, XDN, XSP, or XGR are not equal. If these parameters for the adjacent intervals are equal NO answer, decision element 438 next asks whether the average slope of the shale line (AVSLP) for the previous interval is greater than zero and whether ϕ_{NCL} for the interval under consideration $(\phi_{NCL})_M$ is greater than zero and whether AVSLP and the slope of the shale line for the present interval differ by more than 7%. If the answer NO, decision element 440 determines whether the average GR_{SH} (AVGRSH) is greater than zero and whether GR_{SH} for this interval $(GR_{SH})_M$ is greater than zero and whether AVGRSH the value of GR_{SH} for the present interval differ by more than 15%. If the answer is NO, decision element 442 asks whether the average ϕ_{MAX} (AVϕMAX) and ϕ_{MAX} of the present interval, $(\phi_{MAX})_M$ are greater than zero and whether the average ϕ_{MAX} (AV ϕMAX) and $\phi_{MAX\,(M)}$ differ by more than 15%. If the answer NO, decision element 444 next asks if the average REC (AVREC), REC for the interval, $(REC)_M$ and $(\phi_{NCL})_M$ are all greater than zero and whether the products AVREC ϕ_{NCL} 1.5 and $(REC)_M$ $(\phi_{NCL})_M^{1.5}$ differ by more than 30%. If the answer is NO, decision element 446 asks whether the average CP (AVCP) and $(CP)_M$, CP for the present interval is greater than zero and whether the AVCP and $(CP)_M$ differ by more than 10%. If the answer again is NO, the two consecutive intervals are considered to have similar characteristics and the intervals are combined by computing new weighted averages of their parameters as represented by block 448. If the interval being considered is not the last interval, NO answer from decision element 450, the program returns to block 434 where the interval is incremented and the parameters of the next consecutive interval are compared to the parameters of the merged interval using the techniques described above.

If a YES answer results from any decision element 436 through 446, the program proceeds to decision element 452 which asks whether there are any previous adjacent intervals which have been found to have similar parameters. Also, if there is YES answer from decision element 450, the program proceeds to decision element 452. If the answer is YES, the adjacent consecutive intervals with similar parameters are grouped. Parameters which are equal for the consecutive intervals, i.e., ρ_{fl}, R_w, etc., are set to these values for the grouped intervals, and parameters which may differ between the intervals, i.e., CP, ϕ_{MAX}, etc., are set to the weighted averages of these parameters for the grouped intervals. If the answer from decision element 452 is NO, block 454 is bypassed. Next, decision element 456 asks whether the interval being considered is the last interval. If it is not, NO answer, the program returns to block 432 where new weighted averages are computed and the analysis begins again. If this is the last interval, the program returns via block 458.

Finally, values of ϕ_{MAX} and CP are filled in for intervals where they have not been computed using subroutine FILLAR which is described above, block 470 (Fig. 19B) and the program goes to sweep 3, block 472.

Referring now to Figure 22, sweep 3 is shown in detail. Sweep 3 is entered, block 500 and the input parameters including the parameters computed during sweeps 1 and 2 for the first measurement interval (which may now be a merged group of a number of consecutive intervals) are read, block 502. One level of logging data is read, block 504 and the ϕ_N and ϕ_D measurements are corrected for zero shifts, computed in sweep 1, SP is normalized by multiplying by XSP and ϕ_S is corrected for compaction factor, block 506 as is well known in the art. The sand and shale discriminators for the SP measurements are then computed, block 508. Next, decision element 510 asks whether ϕ_N is less than 0.05 or whether ϕ_D is less than zero. If the answer is YES, no analysis is done for the depth level and the program proceeds to decision element 512 which asks whether this was the last depth level in the interval. If the answer is NO, the depth is incremented, block 514 and the program returns to block 504 to begin the analysis of the next depth level.

If the answer from decision element 510 is NO, the program proceeds to decision element 516 which after applying the fast-break discriminators to ϕ_S, ϕ_N and ϕ_D asks whether ϕ_D/ϕ_N is greater than 0.7; or whether XGR is greater than zero and GR less than DAX; or R_t greater than RESH. If the answer is NO, M_1 and N_1 are computed using equations 84 and 85, respectively, block 518 after which decision element 520 asks whether M_1 is greater than $N_1/3+0.65$. If the answer is NO, decision element 522 next asks whether the difference between ϕ_{MAX} and ϕ_D is less than 0.01 or whether XSP is not equal to zero and whether SP is greater than 0.5 $(SP_{SD}+SP_{SH})$. If the answer is NO, an array for computing ϕ_{NSHO} is entered with an index proportional to ϕ_{MAX}, ϕ_N and ϕ_D, block 524. If the answer from decision element

522 is YES, block 524 is bypassed. Next, decision element 526 asks whether XSP is not equal to zero and whether SP is greater than the SP shale discriminator. If the answer is NO, two arrays for computing ϕ_{NCL} and ϕ_{DCL} are entered with indices proportional to ϕ_D and ϕ_N block 528.

If there is a YES answer from any of decision elements 516, 520, or 526 or after the operation represented by block 528, the program proceeds to decision element 530 which asks whether ϕ_D is less than 0.05; or whether ϕ_N is greater than 0.45; or whether ϕ_D is greater than 0.45; or whether ϕ_D/ϕ_N is less than 0.7; or whether $(\phi_N-\phi_D)$ is greater than 0.01; or whether CAL is greater than CAL_{MAX}; or whether XGR is greater than zero and GR is greater than DALIM; or whether XSP does not equal zero and SP is less than SP_{SDL}. If the answer is NO, a 45 cell array for computing ϕ_{MAX} is entered, block 532 and the appropriate index computed. Next, decision element 534 asks whether R_t is less than 0.05 or whether R_{wv} is greater than 2_{RWmax}. If the answer is NO, the value of the temperature factor F is computed using equation 102, block 536 and three 50-cell arrays are entered for computing respectively R_w (ϕ_D), R_w (ϕ_N) and R_w (ϕ_S), block 538 by computing the appropriate indices.

The program next proceeds to decision element 540 which asks whether ϕ_D is less than ϕ_N. If it is, YES answer, the apparent resistivity of the mud filtrate R_{mfs} is computed using equation 105, block 542, and if the answer is NO, R_{mfs} is computed using equation 106, block 544. A 50-cell array is next entered for computation of R_{mf} for the entire log, block 546 with the index computed using the R_{mfs} value computed above.

Either via YES answers from decision element 530 or 534 or from block 546 the program proceeds to block 512 which determines whether this was the last depth level in the interval. If it is not, the program returns to block 504 for analysis of the next depth level. If this was the last depth level in the interval, YES answer, X_{MAX} for the ϕ_{MAX} array and X_{MIN} for the ϕ_{NCL}, ϕ_{DCL}, ϕ_{NSHO} and R_{wa} arrays are determined, block 548 and ϕ_{MAX}, ϕ_{NCL}, ϕ_{DCL}, ϕ_{NSho}, R_w $(_D\phi)$ and R_w (ϕ_N) and R_w (ϕ_S) for the interval are computed using equations 77, 94, 95, 96, 98, and 103, respectively, block 550. If this is not the last interval in the logging interval, NO answer from decision element 552, the program proceeds to the next interval, block 554 and returns to block 502 for analysis for that interval.

After all the intervals have been analyzed, YES answer from decision 552, X_{MAX} from the R_{mf} array is determined, block 556 and R_{mf} of the entire logging interval is computed using equation 107, block 558. Then, subroutine FILLAR, Fig. 18 is called to fill in missing values of ϕ_{MAX}, ϕ_{NCL}, ϕ_{DCL} and ϕ_{NSho}, block 560.

Prior to proceeding to sweep 4, the computed values of ϕ_{NSho}, ϕ_{NCl} and ϕ_{DCl} for each interval are checked to insure that they conform to the shaly sand model. This is represented by block 562 and the CHECK COMPUTED PARAMETERS subroutine, Fig. 23. Referring now to Fig. 23, the subroutine is entered via block 570 and the computed parameters for one interval are read, block 572. The slope of the shale line ϕ_{NCl}/ϕ_{DCl} called SLOPE is computed, block 574. The slope of the shale line, ϕ_{NCl}/ϕ_{DCl} remains constant for the remainder of the computations. ϕ_{NC} is then computed using equation 108, block 576. Next, decision element 578 asks if ϕ_{NC} is greater than 0.13 and if it is not, NO answer, ϕ_{NC} is set equal to 0.13, block 580 and ϕ_{NCl} and ϕ_{DCl} computed, using equations 109 and 110, block 582. If ϕ_{NC} is greater than 0.13, block 578 and 580 are bypassed. The silt index, SI is next computed using equation 111, block 584. Decision element 586 next asks if SI is greater than 0.5 and if it is not, decision element 588 asks if ϕ_{NC} is greater than 0.2. If the answer from decision element 588 is NO, ϕ_{NC} is set equal to 0.2, block 590 and ϕ_{NCl} and ϕ_{DCl} are recomputed, block 592 using equations 112 and 110, respectively. If there is a YES answer from either decision elements 586 or 588, block 592 is bypassed.

Next, SI is again computed using equation 111, block 594 and if it is not greater than 0.3, NO answer from decision element 596, the program proceeds to decision element 598 which determines whether ϕ_{NSho} is greater than $(\phi_{MAX}+0.01)$. If it is, YES answer, ϕ_{NSho} is set equal to $(\phi_{MAX}+0.01)$, block 600, otherwise block 600 is bypassed.

SI is next again computed using equation 111, block 602 and if is still not greater than 0.3, which is asked by decision element 604, decision element 606 asks if ϕ_{NC} is greater than ϕ_{MAX}. If the answer is YES, ϕ_{NSho} is set equal to 0.7 ϕ_{NCL}, block 620. If the answer is NO, decision element 608 next asks if ϕ_{MAX} is greater than 0.3. If it is not, ϕ_{NC} is set equal to ϕ_{MAX}, block 610 while if it is, YES answer, ϕ_{NC} is set equal to 0.3, block 612. In either event, ϕ_{NCl} and ϕ_{DCl} are computed again using equations 113 and 110, respectively, block 614 and the value SI is again computed using equation 111, block 616. Decision element 618 next asks if SI is greater than 0.3 and if is not, ϕ_{NSho} is set equal to 0.7 ϕ_{NCl}, block 620.

If there is a YES answer from either decision element 596 or 604 or after block 620, the program proceeds to decision element 622 which determines whether this was the last interval, if it was not, NO answer, the program proceeds to analyze the next interval via blocks 624 and 572. After all the intervals have been checked, the program returns, block 626, and goes to sweep 4, block 630 (Fig. 22).

Referring now to Fig. 24, sweep 4 is shown in detail. Sweep 4 is entered via block 660. The input parameters for the first interval are read, block 662, and logging data for the first depth level is also read and corrected, block 664, as in sweep 3.

Next, decision element 666 applies the fast-break discriminators to ϕ_S, ϕ_D and ϕ_N and also asks if CAL is greater than CAL_{MAX}; or if ϕ_N is less than 0.05; or if ϕ_D is less than -0.02. If the answer is YES, the program proceeds to decision element 668 which asks if this is the last depth level in the interval. If it is not, NO answer, the depth is incremented, block 670 and the program returns to block 664 for analysis of the next depth level. If the answer is NO, ϕ_e, V_{SH} and SI are computed using a simplified shaly sand model as represented by block 672. The analysis is carried by subroutine SARAN which is shown in greater detail in Fig. 25.

Referring now to Fig. 25, subroutine SARAN is entered via block 680 and SI is computed using equation 111, block 682. Decision element 684 next asks if ϕ_D is greater than ϕ_N and if it is, V_{SH} is set equal to zero, block 686, ϕ_e is computed using equation 115, block 688, and the subroutine returns, block 690.

If the answer from decision element 684 is NO, decision element 692 next asks if ϕ_D is less than ϕ_N

$$\frac{\phi_{DCl}}{\phi_{NCl}}$$

and if the answer is NO, decision element 694 next asks if ϕ_N is greater than

$$1-(1-\phi_D)\left[\left(\frac{1-\phi_{NCl}}{1-\phi_{DCl}}\right)\right]$$

and if the answer is YES, ϕ_N is set equal to:

$$1-(1-\phi_D)\left[\left(\frac{1-\phi_{NCl}}{1-\phi_{DCl}}\right)\right]$$

block 696. If the answer decision element 694 is NO, block 696 is bypassed. As represented by block 698, ϕ_e is now set equal to:

$$\frac{\phi_D\,\phi_{NCl}-\phi_N\,\phi_{DCl}}{\phi_{NCl}-\phi_{DCl}}$$

and V_{Cl} is set equal to:

$$\frac{\phi_N-\phi_D}{\phi_{NCl}-\phi_{DCl}}$$

Decision element 700 next asks if ϕ_e is equal to or greater than

$$\phi_{MAX}\,[1-V_{Cl}{}^2\,(2-V_{Cl})]$$

If the answer is YES, V_{sh} is set equal to V_{Cl} and SI is set equal to zero, block 702 and the program returns to block 690. If the answer is NO, V_{sh} is set equal to

$$\frac{V_{Cl}}{1-SI}$$

block 704 and decision element 706 asks if V_{sh} is greater than 1 or ϕ_e is greater than or equal to:

$$\phi_{MAX}\ [1-V_{sh}^2\ (2-V_{Sh})]$$

If the answer is NO, the program returns via block 690. If the answer is YES, the program proceeds to decision element 708 which asks if ϕ_e/ϕ_{MAX} is less than 0.75. If it is, YES answer, V_{sh} is computed using equation 119, block 710 and if it is not, V_{sh} is computed using equation 120, block 712. Next, decision element 714 asks if V_{sh} is less than V_{Cl} and if it is, V_{Sh} is set equal to V_{Cl} and SI is set equal to zero, block 702 and the program returns block 690. If V_{sh} is not less than V_{Cl}, NO answer from decision element 714, SI is computed using equation 121, block 716 and the program returns via block 690.

Referring now decision 692, if ϕ_D is less than

$$\phi_N \frac{\phi_{DCl}}{\phi_{NCl}}$$

YES answer, ϕ_e is set equal to zero and V_{sh} is set equal to one, block 718. Decision elements 720 next asks if ϕ_N is less than ϕ_{NSh_0} and if it is, YES answer, the program returns, block 690. If the answer is NO, SI is computed using equation 116, block 722. If SI is less than zero, YES answer from decision element 724, SI is set equal to zero, block 726 and in either event, the program returns via block 690.

After computation of ϕ_e, V_{sh} and SI using SARAN, the program returns to decision element 730, Fig. 24, which asks if V_{sh} is less than 0.6; whether XGR is greater than zero and GR is less than DAX; or whether XSP is greater than zero and SP is greater than SP_{SH1}. If the answer is NO, M_1 and N_1 are computed using equations 144 and 145, respectively, block 732 and decision element 734 next asks if M_1 is greater than $0.35\ N_1+0.55$ or whether R_t is greater than RESH. If the answer is NO, the decision element 736 asks if R_w is less than or equal to $1.25\ \phi_e^2\ R_t\ (1-V_{sh})$ and if the answer is again NO, the value of R_{Cl} is computed using equation 123, block 737. A running sum of R_{Cl} in the interval is computed as represented by block 738. If the answer to decision elements 736 is YES, blocks 737 and 738 are bypassed.

Next, decision element 740 asks if XGR equals zero and if not, the GR and VSH measurements for the depth level are used in computation of a running sum of GR and V_{sh} for shale levels in the interval, block 742. If XGR equals zero, block 742 is bypassed. Similarly, if XSP does not equal zero, NO answer from decision element 744, the SP and V_{sh} measurements for the depth level are used in computing a running sum of the SP and V_{sh} for shale levels in the interval, block 746 and if XSP does not equal zero, block 746 is bypassed.

The program now proceeds to decision element 748 either via decision 730 or 734 or block 746. Decsion element 748 asks if V_{sh} is greater than 0.25 or whether ϕ_D/ϕ_N is less than 0.6. If the answer is YES, the program proceeds to decision element 668 which asks if this is the last depth evel in the interval and if it is not, the next depth level is analyzed via block 670 and 664. If the answer from decision element 748 is NO, decision element 750 asks if XSP equals zero, or if SP is less than SP_{SDL}, or if SP is greater than $SP_{SD}+10$. If the answer from decision element 750 is NO, the value of SP and V_{sh} for the depth levels are used to compute a running sum of SP and V_{sh} for sand levels in the interval, block 752. If the answer from decision element 750 is YES, block 752 is bypassed. Similarly, decision element 754 asks if XGR equals zero, or if GR is greater than DALIM and if the answer is NO, the value of GR and V_{sh} for the depth level are used in the computation of a running sum for GR and V_{sh} for sand levels in the interval, block 756. If the answer from decision element 754 is YES, block 756 is bypassed.

Next, decision element 758 asks if R_{wv} is greater than $2R_{wvmax}$. If the answer is NO, a 50-cell array for computing R_w-QL is entered with an index value dependent on R_{mf} and R_{xo}/R_t, block 760. If the answer from decision element 758 is YES, block 760 is bypassed. The analysis of the depth level is now complete decision element 668 asks if this is the last depth level in the interval. If it is not, the program returns to block 664 via block 670.

If all the depth levels in the interval has been analyzed, YES answer from decision element 668, the average values of the sum R_{Cl}, GR_{Sh}, VG_{Sh}, GR_{Sd}, VG_{Sd}, are computed for the interval from the running sums, block 762. Next, GR_{SD} and

GR_{SH} are computed using equations 75 and 76, respectively, block 764 and then DAX and DALIM are computed using equations 66, 67, block 766. Then, the average value of the sums, SP_{SD}, VS_{SD}, SP_{SH} and VS_{SH} are computed, block 768 and SP_{SD} and SP_{SH} are computed using equations 127 and 127a, block 770. As represented by block 772, the SP measurements are normalized with the value of XSP for the interval.

R_w is now computed using the value of SP_{SD} (block 774). This operation is shown in greater detail in Fig. 26. Referring now to Fig. 26, the subroutine is entered via block 780, and decision element 782 asks if $R_{mf}(75)$ is greater than 0.3. If it is, the parts per million times 10^6 of sodium chloride in the mud filtrate, PPM_{mf} is computed according to equation 128, block 784 and if it is not, PPM_{mf} is computed according to equation 129, block 786. Then parts per million times 10^6 of sodium chloride in water, PPM_w is computed using equations 129a, 130 and 131, block 786 and if the PPM_w is less than 0.02 which question is asked by decision element 788, R_w is computed using equation 132, block 790. Otherwise, R_w is computed using equation 133, block 792 and the program returns, block 794.

Referring back to Fig. 25, X_{MIN} is next determined from the R_w—QL array, block 800 after which R_w—QL is computed using equation 103, block 802. If this is not the last interval, NO answer from decision element 804, the program goes to the next interval, block 806 and returns to block 662 where the analysis of the next interval begins. After all the intervals have been analyzed, the program prints out the values of the computed parameters and also can automatically punch the input cards required for running the interpretation program, as represented by block 808, before exiting, block 810.

While there has been described what is at present considered to be preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein.

Attention is directed to our co-pending United Kingdom Patent Application No. 55330/73, (Serial No. 1,457,758), of which the present application is a divisional application.

WHAT WE CLAIM IS:—

1. A method for automatically determining a correction factor useful for evaluating earth formations traversed by a borehole, comprising:

deriving measurements of a plurality of subsurface characteristics at different depth levels in a section of the borehole;

using at least some of said measurements to automatically select a set of less argillaceous depth levels in the borehole section;

producing a function of first and second parameters derived from measurements of first and second subsurface characteristics at said selected depth levels;

modifying at least the first parameter at said selected depth levels by a first variable correction factor; and,

determining a value of said first correction factor which optimizes said function to correct said first parameter.

2. The method of claim 1, wherein the less argillaceous levels are selected in accordance with measurements of natural gamma ray and/or spontaneous potential at depth levels of the borehole section.

3. The method of claim 1 or 2, wherein the step of selecting further comprises performing a secondary selection of water bearing levels among the less argillaceous depth levels.

4. The method of any one of claims 1 to 3, wherein said first parameter is representative of measurements at said selected depth levels of said first subsurface characteristic of the formation, and the determined value of said first correction factor is used for calibrating measurements of said first characteristic.

5. The method of claim 4, wherein said first parameter is representative of neutron porosity measurements at said selected levels.

6. The method of any one of claims 1 to 5, wherein said correction factor represents a shift of the scale of said parameter.

7. The method of any one of claims 1 to 5, wherein said correction factor is a multiplication factor corresponding to a change in sensitivity of the scale of said parameter.

8. The method of any one of claims 1 to 3, wherein said first parameter is a function of a value of a subsurface characteristic valid over the borehole section and the corresponding value determined for said first correction factor is used for obtaining an improved value of said subsurface characteristic in the borehole section.

GR_{SH} are computed using equations 75 and 76, respectively, block 764 and then DAX and DALIM are computed using equations 66, 67, block 766. Then, the average value of the sums, SP_{SD}, VS_{SD}, SP_{SH} and VS_{SH} are computed, block 768 and SP_{SD} and SP_{SH} are computed using equations 127 and 127a, block 770. As represented by block 772, the SP measurements are normalized with the value of XSP for the interval.

R_w is now computed using the value of SP_{SD} (block 774). This operation is shown in greater detail in Fig. 26. Referring now to Fig. 26, the subroutine is entered via block 780, and decision element 782 asks if $R_{mf}(75)$ is greater than 0.3. If it is, the parts per million times 10^6 of sodium chloride in the mud filtrate, PPM_{mf} is computed according to equation 128, block 784 and if it is not, PPM_{mf} is computed according to equation 129, block 786. Then parts per million times 10^6 of sodium chloride in water, PPM_w is computed using equations 129a, 130 and 131, block 786 and if the PPM_w is less than 0.02 which question is asked by decision element 788, R_w is computed using equation 132, block 790. Otherwise, R_w is computed using equation 133, block 792 and the program returns, block 794.

Referring back to Fig. 25, X_{MIN} is next determined from the R_w—QL array, block 800 after which R_w—QL is computed using equation 103, block 802. If this is not the last interval, NO answer from decision element 804, the program goes to the next interval, block 806 and returns to block 662 where the analysis of the next interval begins. After all the intervals have been analyzed, the program prints out the values of the computed parameters and also can automatically punch the input cards required for running the interpretation program, as represented by block 808, before exiting, block 810.

While there has been described what is at present considered to be preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein.

Attention is directed to our co-pending United Kingdom Patent Application No. 55330/73, (Serial No. 1,457,758), of which the present application is a divisional application.

WHAT WE CLAIM IS:—

1. A method for automatically determining a correction factor useful for evaluating earth formations traversed by a borehole, comprising:

deriving measurements of a plurality of subsurface characteristics at different depth levels in a section of the borehole;

using at least some of said measurements to automatically select a set of less argillaceous depth levels in the borehole section;

producing a function of first and second parameters derived from measurements of first and second subsurface characteristics at said selected depth levels;

modifying at least the first parameter at said selected depth levels by a first variable correction factor; and,

determining a value of said first correction factor which optimizes said function to correct said first parameter.

2. The method of claim 1, wherein the less argillaceous levels are selected in accordance with measurements of natural gamma ray and/or spontaneous potential at depth levels of the borehole section.

3. The method of claim 1 or 2, wherein the step of selecting further comprises performing a secondary selection of water bearing levels among the less argillaceous depth levels.

4. The method of any one of claims 1 to 3, wherein said first parameter is representative of measurements at said selected depth levels of said first subsurface characteristic of the formation, and the determined value of said first correction factor is used for calibrating measurements of said first characteristic.

5. The method of claim 4, wherein said first parameter is representative of neutron porosity measurements at said selected levels.

6. The method of any one of claims 1 to 5, wherein said correction factor represents a shift of the scale of said parameter.

7. The method of any one of claims 1 to 5, wherein said correction factor is a multiplication factor corresponding to a change in sensitivity of the scale of said parameter.

8. The method of any one of claims 1 to 3, wherein said first parameter is a function of a value of a subsurface characteristic valid over the borehole section and the corresponding value determined for said first correction factor is used for obtaining an improved value of said subsurface characteristic in the borehole section.

9. The method of claim 8, wherein said first parameter is derived from formation resistivity and said subsurface characteristic value is the formation water resistivity.

10. The method of any one of claims 1 to 9, further comprising:

modifying the second parameter at the selected depth levels by a second variable correction factor; and wherein the determining step comprises determining a combination of values of said first and second correction factors which optimizes said function of the first and second parameters, to use the value of the second factor in the determined combination to correct said second parameter.

11. The method of any one of claims 1 to 10, comprising the following steps:

selecting among the selected depth levels, those for which said function of the first and second parameters satisfies a first given relationship after correcting said first parameter;

producing a second function of at least a third parameter derived from measurements of a third subsurface characteristic at said newly selected levels;

modifying said third parameter by another variable correction factor;

determining a value of said other correction factor which optimizes said second function to correct said third parameter.

12. The method of claim 11, wherein said third parameter is representative of measurements of a third subsurface characteristic, and the determined value of said other correction factor is used for calibrating measurements of said third characteristic.

13. The method of claim 12, wherein said third parameter is representative of measurements of density of the formations.

14. The method of any one of claims 11 to 13, wherein said second function is a function of said second and third parameters.

15. The method of claim 14, further comprising:

producing a third function of said first and third parameters at said newly selected depth levels;

modifying said first and third parameters by new variable correction factors;

determining combinations of values of said new correction factors which optimize said third function; and,

selecting as improved correction factors for said first and third parameters that combination which comes nearest to the values of the correction factors previously determined for said first and third parameters.

16. The method of claim 14, when dependent from claim 10, comprising again modifying the second parameter by the second variable correction factor;

determining another value of said second correction factor that optimizes said second function; and

comparing the determined values of said second correction factor to determine if a scale multiplicative correction factor is required for modifying said first parameter.

17. A method of automatically determining a calibration correction useful for evaluating earth formations traversed by a borehole, comprising:

deriving measurements of a plurality of subsurface characteristics at different depth levels in a section of the borehole;

using at least some of said measurements to automatically select in the borehole section depth levels corresponding to low porosity formations;

detecting a lithological structure at some of said selected depth levels on the basis of parameters derived from said measurements at said selected depth levels; and

determining, on the basis of a known value of a selected characteristic of the formations in the detected lithological structure, a calibration correction to be applied to measurements of said selected characteristic.

18. The method of claim 17, wherein said derived parameters may be the measurements themselves and said lithological structure detecting step comprises:

comparing for each of said selected depth levels, the values of said parameters at said level with corresponding predetermined values, and

performing a new selection of depth levels having the specific lithological structure detected, as a result of said comparison.

19. The method of claim 18, wherein the specific lithological structure detected is anhydrite or salt.

20. The method of claim 17, wherein said lithological structure detecting step comprises:

determining a statistically optimum value for one of said derived parameters at said selected depth levels; and

(63)

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testing said statistically optimum value to detect the presence of at least one known mineral in a substantially pure state at said selected depth levels.

21. The method of claim 20, wherein said parameter is a function of measurements of plurality of characteristics at said selected depth levels, said parameter being representative of a matrix characteristic of the formations.

22. The method of claim 21 or 22, wherein said statistically optimum value is a difference between two extremum values of said parameter.

23. The method of any of claims 20 to 22, wherein said testing step comprises:

determining whether said statistically optimum value satisfies a predetermined relationship to detect if two minerals are present in a substantially pure state among said selected depth levels.

24. The method of any of claims 20 to 22, wherein said testing step comprises:

determining whether said statistically optimum value satisfies a predetermined relationship to detect if one mineral only is present among said selected depth levels, and, if so, determining a second statistically optimum value derived from measurements at said selected depth levels; and,

testing said second statistically optimum value for determining which mineral is present in a substantially pure state among said selected depth levels.

25. The method of claim 24, wherein said second statistically optimum value is a mean value of a function of measurements of a plurality of formation characteristics at said selected depth levels.

26. The method of any of claims 20 to 22, wherein said testing step comprises:

determining whether said statistically optimum value satisfies a predetermined relationship to detect if more than one mineral is present at said selected depth levels; and, if so, deriving statistical data from measurements at said selected depth levels; and,

testing said statistical data to determine if one of the minerals present is substantially in a pure state among said selected depth levels.

27. The method of any one of claims 17 to 26, wherein said calibration correction determination step comprises:

determining a statistically optimum value of a signal derived from measurements of said selected characteristic at said selected depth levels; and

determining a correction to apply to measurements of said selected characteristic for bringing said optimum value of said signal back to another determined value.

28. The method of claim 27, wherein said optimum value is an extremum of said derived signal for the selected depth levels.

29. The method of claim 27, wherein said optimum value is a mean value of said derived signal for said selected depth levels.

30. The method of any one of claims 27 to 29, wherein said other determined value is a known predetermined value of the derived signal for the specific lithological structure detected.

31. The method of one of claims 27 to 29, wherein said other determined value is a statistically optimum value of another signal derived from measurements of another characteristic of formations at said selected depth levels.

32. The method of any one of claims 27 to 31, wherein said derived signal is representative of measurements of said selected characteristic.

33. The method of any one of claims 27 to 31, wherein said derived signal is a function of measurements of a plurality of characteristics at the selected depth levels, representative of a formation matrix characteristic.

34. The method of any of claims 27 to 33, wherein said calibration correction is an additive factor corresponding to a shift of the zero of the scale of the corrected measurements.

35. The method of any of claims 27 to 33, comprising determining, in two specific lithologies, two corrections to be applied to measurements of the selected characteristic and wherein one of said corrections is an additive factor corresponding to a shift of the scale of the corrected measurements and the other of said corrections is a multiplicative factor corresponding to a change in the sensitivity of said scale.

B. D. STOOLE,
Chartered Patent Agent,
Agent for the Applicants.

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