FORMATION POROSITY EXPLORATION

Filed Feb. 4, 1963

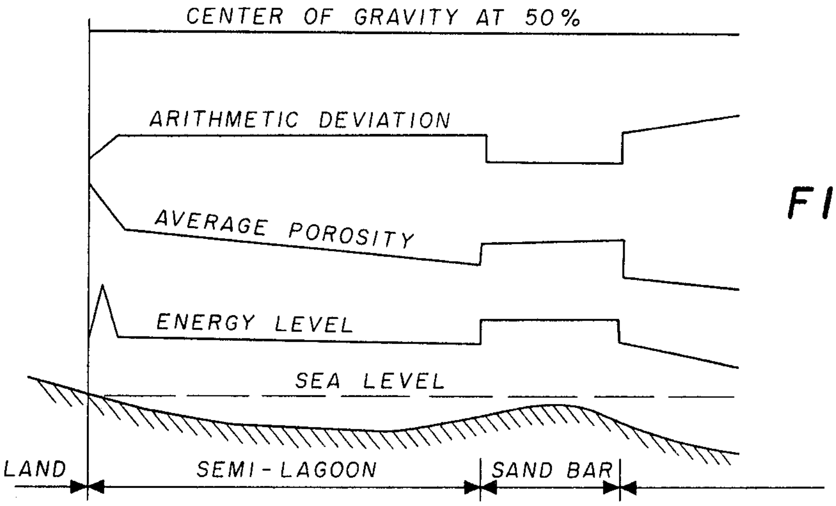
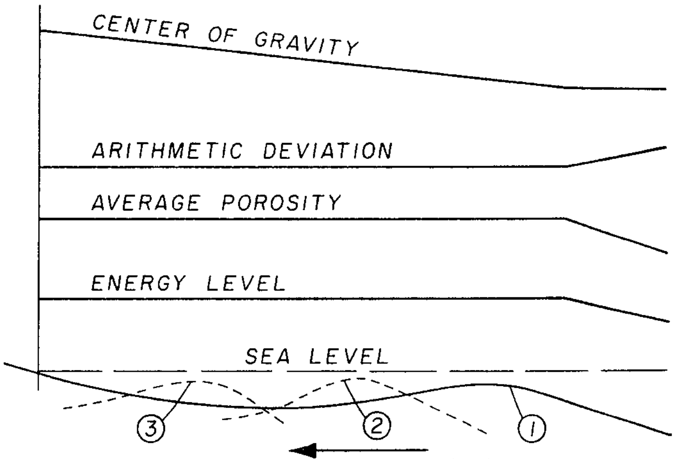


FIG. 1

FIG. 2



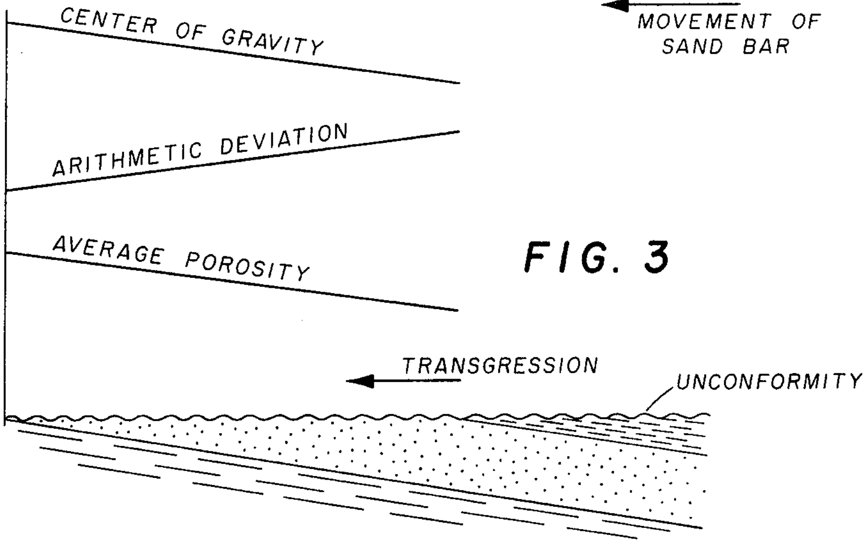


FIG. 3

Aug. 23, 1966 J. A. WINTER **3,268,858**

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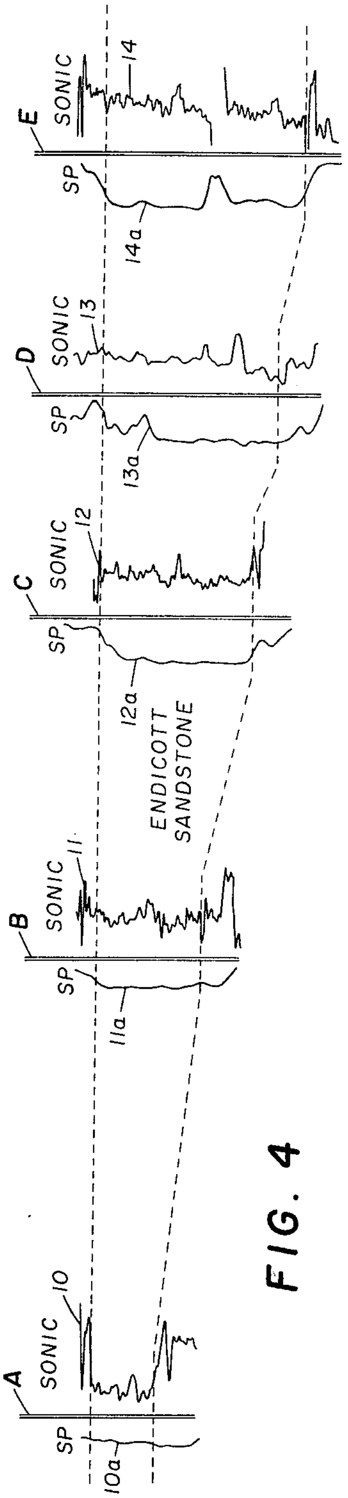

FIG. 4

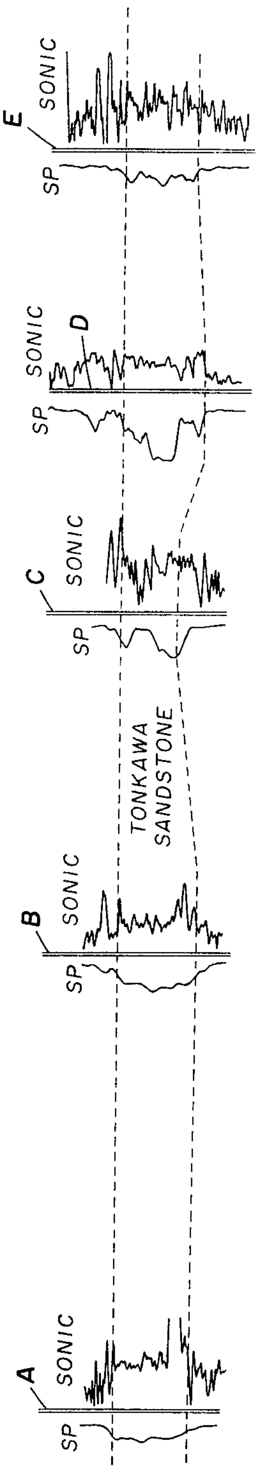

FIG. 5

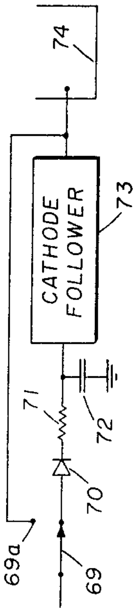

FIG. 6A

FIG. 6

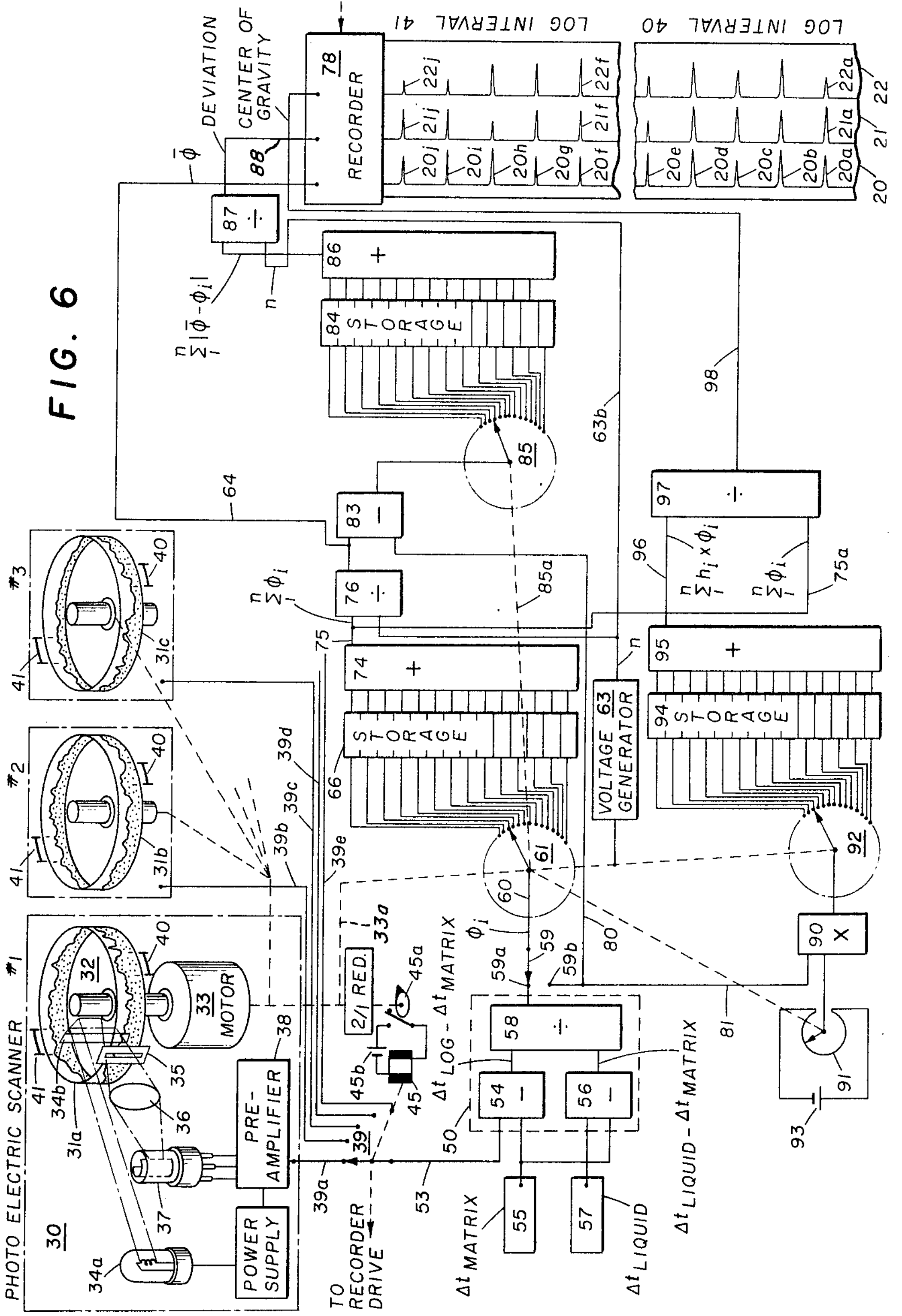
PHOTO ELECTRIC SCANNER
30
#1
#2
#3
31a
31b
31c
32
33
MOTOR
33a
34a
34b
35
36
37
38
PRE-AMPLIFIER
POWER SUPPLY
39
39a
39b
39c
39d
39e
40
41
45
45a
45b
2/1 RED.
TO RECORDER DRIVE
50
53
54
55
56
57
58
59
59a
59b
60
61
63
VOLTAGE GENERATOR
63b
64
66
STORAGE
74
75
75a
76
78
RECORDER
80
81
83
84
85
85a
86
87
88
90
91
92
93
94
95
96
97
98
n
Δt_{MATRIX}
Δt_{LIQUID}
$\Delta t_{LOG} - \Delta t_{MATRIX}$
$\Delta t_{LIQUID} - \Delta t_{MATRIX}$
ϕ_i
$\sum_1^n \phi_i$
$\sum_1^n h_i \times \phi_i$
$\sum_1^n |\bar{\phi} - \phi_i|$
$\bar{\phi}$
DEVIATION
CENTER OF GRAVITY
LOG INTERVAL 40
LOG INTERVAL 41
20
21
22
20a
20b
20c
20d
20e
20f
20g
20h
20i
20j
21a
21f
21j
22a
22f
22j

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FORMATION POROSITY EXPLORATION

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FIG. 7 STRUCTURE

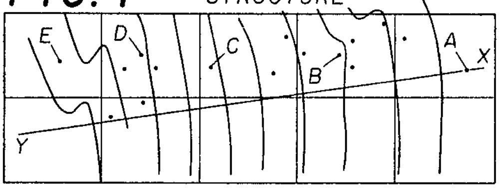


FIG. 8 ISOPACH

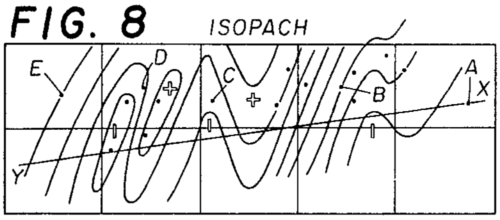


FIG. 9 ($\bar{\phi}$) AVERAGE POROSITY

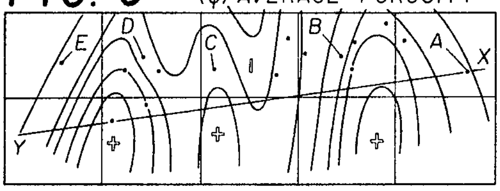


FIG. 10 (A D) DEVIATION

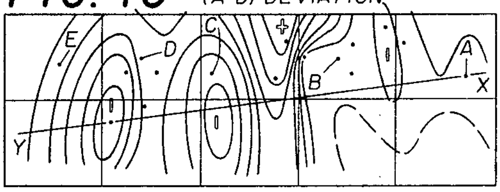


FIG. 11 (C G) CENTER OF GRAVITY

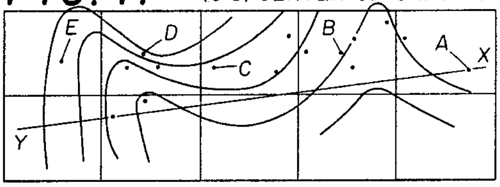


FIG. 12 STRUCTURE

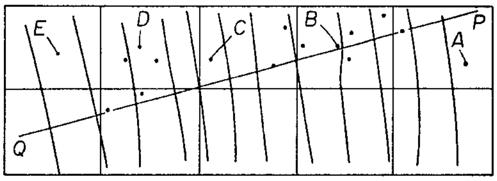


FIG. 13 ISOPACH

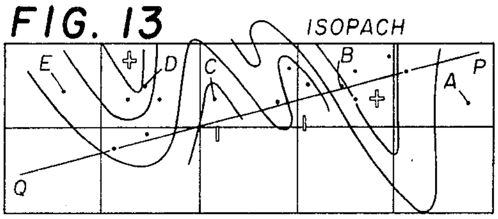


FIG. 14 ($\bar{\phi}$)

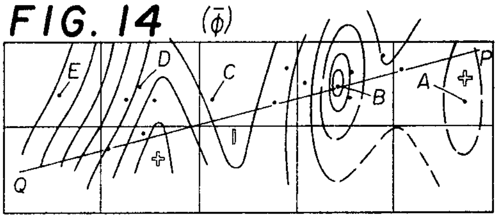


FIG. 15 (A D)

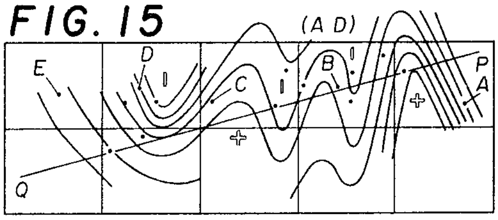


FIG. 16 (C G)

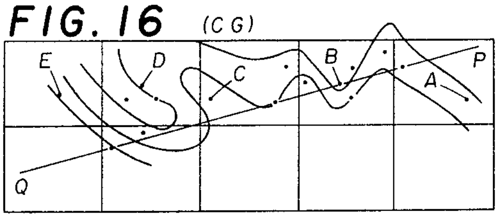


FIG. 17

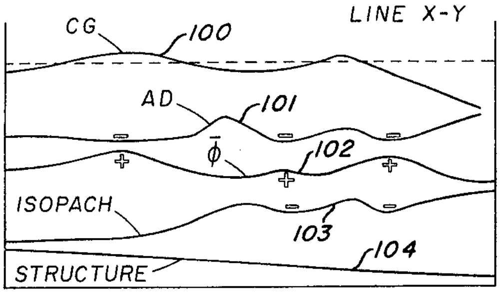
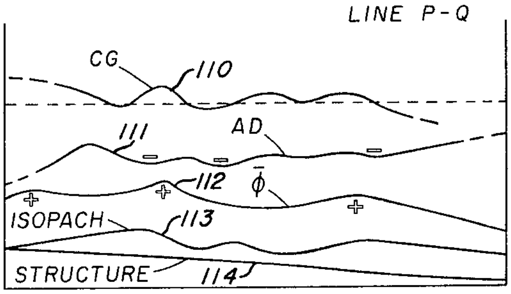


FIG. 18



3,268,858
FORMATION POROSITY EXPLORATION

Jan A. Winter, Tulsa, Okla., assignor to Century Geophysical Corporation, Tulsa, Okla., a corporation of Delaware

Filed Feb. 4, 1963, Ser. No. 255,760
16 Claims. (Cl. 340—15.5)

This invention relates to the production of indicia as to the location of areas favorable to hydrocarbon accumulation and, more particularly, to the evaluation of subterranean trends exhibiting a characteristic porosity function.

The many endeavors to provide an understanding for the character of the earth's lithology, the location of anomalous zones within the earth's crust, the reasons for the occurrence of such anomalies, and the behavior of such anomalies in connection with the exchange of liquid and solid constituents in the earth's formations over large periods of time have led to the development of many and varied tools. Geophysicists and geologists employ every measurement capable of yielding an additional bit of information relating to the lithological character of the earth's crust. This is particularly the case in the search for minerals and particularly for deposits of hydrocarbons.

The refinement of exploratory techniques such as radioactivity logging, electrical logging and acoustic logging has provided tools which have been mainly used by geophysicists and reservoir engineers and geologists primarily as a correlation tool. In connection with each of the foregoing types of logging operations, theoretical considerations have led to the determination of a factor or parameter of the earth's crust which is of significance. This factor is that of the porosity of the earth's formations. Many and varied have been the interpretive techniques applied to the formation dependent data represented by radioactive, electrical and acoustic logs.

The present invention relates to an exploration technique and the development of additional parameters based upon a porosity function for revealing the structural character of the earth's formations and particularly those areas and trends in those areas of porous nature which are likely or possibly will contain accumulations of hydrocarbons.

More particularly, in accordance with the present invention, there is provided a method of determining the time-structural development of subterranean earth formations. Included in the method are the steps of measuring an earth dependent function of a lithologic body along at least two laterally spaced, vertically directed lines extending to the body of interest. The function is then modified to produce a porosity function of the body. From the porosity function there is then established a numerical value of the deviation from an average of the porosity functions over the thickness of the body at the location of each of the said lines and the deviation function is then registered in correlation with the location of the lines.

In accordance with a further aspect of the invention, a further function is developed, namely, a function representative of the center of gravity of the body. The location of the center of gravity is plotted in correlation with said locations.

In a preferred embodiment of the invention, an incremental acoustic velocity function of a given lithologic body is produced for each of at least two vertically oriented traverses through the body with the porosity function for each of said locations being developed from the incremental acoustic velocity function. From the porosity function the arithmetic deviation of the porosity function over the section is developed along with the deviation from the center of the body of the center of gravity. The latter two functions are then plotted as a function in correlation with the location of the two lines through the body to provide a measure of the movement of characteristic sections of the body in the course of its initial development.

It is to be understood that the invention relates to the application of statistical methods to porosity information available from earth dependent geophysical logs to establish a criteria for determination of the origin of given lithologic bodies.

For a more complete understanding of the present invention and for further objects and advantages thereof, reference may now be had to the following description taken in conjunction with the accompanying drawings in which:

FIGURE 1 is a theoretical profile for detrital units with stationary shoreline and sand bar;

FIGURE 2 is a similar profile with a sand bar and shoreline moving toward a source area;

FIGURE 3 is a similar profile located below an unconformity under leaching conditions;

FIGURE 4 is a velocity log profile for five holes along a given traverse showing an Endicott sandstone section from Oklahoma;

FIGURE 5 is a velocity log profile showing Tonkawa sandstone in Oklahoma in the same holes as in FIGURE 4;

FIGURE 6 illustrates a system for generating conditions indicative of forces and movements present during the building of the sandstone beds of FIGURES 4 and 5;

FIGURE 6*a* is a more detailed circuit diagram of one of the storage units in the storage bank 66 of FIGURE 6.

FIGURE 7 is a structure contour map of the top of the Endicott sandstone over the area covered by the profile of FIGURE 4;

FIGURE 8 is an isopach map of the same area as FIGURE 7;

FIGURE 9 is an average porosity map of Endicott sandstone from data produced in FIGURE 6 for the same area as in FIGURE 7;

FIGURE 10 is an arithmetic deviation map of the porosity in the Endicott sandstone;

FIGURE 11 is a plot of center of gravity of the Endicott sandstone for the same area as in FIGURE 7;

FIGURE 12 is a structure contour map of the top of the Tonkawa sandstone over the area covered by the profile of FIGURE 5;

FIGURE 13 is an isopach map of the same area as FIGURE 12;

FIGURE 14 is an average porosity map of Tonkawa sandstone from data produced in FIGURE 6 for the same area as in FIGURE 12;

FIGURE 15 is an arithmetic deviation map of the porosity in the Tonkawa sandstone;

FIGURE 16 is a plot of center of gravity of the Tonkawa sandstone for the same area as in FIGURE 12;

FIGURE 17 is a summary set of profiles for the data of FIGURES 7–11 along the line X–Y taken therethrough; and

FIGURE 18 is a summary set of profiles for the data taken along the line P–Q of FIGURES 12–16.

In order to understand the present invention, it will be helpful to consider briefly the conditions which, in the origin of a given subterranean body, affect the structural features thereof, such as the porosity. The factors which are primary in their effect on porosity and the corresponding geologic agents or conditions responsible for them are as set out in Table I.

TABLE I.—FACTORS AFFECTING PRIMARY POROSITY

Factor	Geologic Condition or Agent
1. Grain size	Distance from source; depositional environment, energy level of environment.
2. Sorting	Wave action; energy level of environment.
3. Grain geometry	Source material; distance from source energy level of environment.
4. Cementation	Percolating waters. (This can either by pre- or post-lithification).
5. Compaction	Overburden pressure and/or tangential pressure. (Mainly post-lithification).

It should be understood that the foregoing factors set forth in Table I are those which affect the primary porosity. A distinction has to be made between primary porosity resulting from voids which are left between the mineral grains and fragments after their accumulation as sediments and secondary porosity resulting from geologic agents acting after lithification of the sediments. The factors and geologic conditions or agents which affect secondary porosity are as follows:

TABLE II.—FACTORS INFLUENCING SECONDARY POROSITY

Factor	Geologic Condition or Agent
6. Cementation	Percolating waters.
7. Leaching	Do.
8. Jointing	Consolidation contraction; tectonic stresses; mineralogical changes; rock-type.
9. Fracturing	Tectonic stresses; rock-type.
10. Compaction	Overburden pressure; tectonic stress.
11. Mineralogical changes	Percolating waters; overburden pressure; tectonic stress; temperature.

Of the factors listed above, it would appear that the grain size, sorting, grain geometry, cementation, and leaching are the most important contributors to porosity variations.

Examination of these factors in terms of geology reveals that the following geological agents or conditions are primarily responsible:

(a) Distance from source area;
(b) Depositional environment and energy level of environment;
(c) Percolating waters.

For any given area with marine sediments it may be said that the distance of the source area can be expressed as a simple function and that consequently the porosity changes due to this condition should be expressed by simple contour patterns. The energy environment, a factor that assumes more and more importance in the eyes of the exploration geologist, may change rapidly and in a complex manner. These changes then lead to local anomalies in the porosities changes and their proper interpretation can lead the favorable areas of hydrocarbon accumulation.

The third and in many cases the most important factor influencing porosity changes is the action of percolating waters. The changes can either be in a positive sense (increase of the original pore space) or negative sense (decrease of the original pore space).

Porosity changes in a positive sense are the result of percolating waters leaching out the more soluble constituents of the rock; whereas changes in a negative sense are effected by percolating waters depositing material in the original pore space.

Percolating waters are to a large extent a near-surface phenomena; consequently, porosity changes due to percolating waters in sedimentary rocks now buried under a considerable thickness of younger strata had to be at one time or other close to the surface after lithification. The proximity to the surface of indurated rocks in turn can signify the presence of geologic unconformities in the stratigraphic column.

It has been found that maps portraying selected functions of porosity changes lead to a wholly new and most useful interpretation of the structural features of the subsurface formations. They lead to a more detailed knowledge of the geologic history of the area or basin in which the body of interest is found and thus permit more successful exploration for minerals such as hydrocarbons.

As an example, the conditions set forth in FIGURES 1–3 illustrate several geological possibilities which give rise to porosity anomalies the origin of which, in accordance with the present invention, can be delineated.

In FIGURE 1 there is illustrated the condition wherein a sand bar, now buried substantially within the stratigraphic column, was, during its formation, stationary in the sense that the bar grew in height as an accumulation of debris was deposited at that site without lateral change in the location of the predominant characteristics of the bar such as its crown and its axis. In the formation of such structures, it can readily be postulated that the energy level of the wave action would be high over the sand bar itself as well as at the shoreline. Thus, an energy level curve has been postulated in FIGURE 1 representing the variation in the energy of the formation forming forces. In such an environment the sorting and rounding of individual grains will be understood to be more thorough than in environments where the energy level is lower. Consequently, the values of porosity and the magnitude of deviation from an average porosity will be indicative of areas of high energy. Furthermore, if the bar should remain stationary during the period of its formation, its center of gravity should be found at the middle of the section thereof. Thus the two curves have been postulated for such a condition, the first being the arithmetic deviation from average porosity and the center of gravity of the section under consideration. By reason of the wave action during structure formation, the average porosity should show a regional decrease in porosity as one moves away from the source of the deposited debris such as at the shoreline. Thus, an average porosity curve has been illustrated, decreasing with distance away from the shoreline.

In FIGURE 2 there is illustrated a case in which it is postulated that a sand bar during formation moves progressively toward the source area, such as the shoreline. The theoretical profiles for such action and such structural activity are illustrated. Under ideal conditions the sand bar may be considered to move equal distances per unit of time. The momentary porosity anomaly will occupy each location along the line through which the section is taken in FIGURE 2, thus eliminating any porosity anomaly in any one location. The same considerations are true for the deviation function. During the accumulation the sand bar location will be present higher in the section than in any previous location. This condition may be detected by variations in the center of gravity which should have a decreasing depth in the section as the bar moves toward the source area or the shoreline. The movement of the center of gravity, of course, is in the opposite direction in the case where the sand bar undergoes regressive movement or movement away from the shoreline. In FIGURE 2 the energy level function, the average porosity function, the deviation function and the center of gravity function are postulated for the structural activity involved as the bar moves toward the shoreline.

In FIGURE 3 there is illustrated the condition wherein a detrital unit is positioned below an unconformity under leaching conditions. The postulated condition is that there is a slow and uniform transgression over a surface of erosion. The right-hand side of the figure will be covered with debris earlier with the younger sediments on the left-hand side of the figure being exposed for a longer period. Consequently, leaching will continue longer on the left-hand side which, in turn, will enlarge the original pore space to a greater extent. Under such conditions it could be postulated that the average porosity will increase in the direction of the transgression and thus, because of this, the deviation may be postulated as an increasing function in the direction of transgression. Further, since the leaching will be predominantly in the higher part of the section, the center of gravity will be above the center of the section and the values of the center of gravity function will decrease in the direction of the transgression.

The foregoing examples have been given in order to provide a basis for understanding the acquisition and use of geophysical data to produce functions such as the deviation in porosity and the location in the section of the center of gravity. Both functions are particularly indicative of the character of action present during the building of given sections of interest. Further, an indication is obtained of the direction to proceed from stations of observation of geophysical data to locations where accumulation of hydrocarbons might be most likely to be encountered.

Thus, in accordance with the present invention, there is provided a function representative of the average porosity of a given section of a lithologic column in at least two laterally spaced zones. A further function representative of the deviation from average porosity for each of the locations is then registered in correlation with the locations of the two spaced apart points. Further, and in a preferred embodiment of the invention, there is also registered a third function representative of the position of the center of gravity of the section of interest. In a preferred mode of carrying out the invention, the foregoing parameters are derived from acoustic velocity logs of a plurality of boreholes at spaced points over a basin in which a given formation is encountered. Preferably, the sections to be studied will be sands in which the formations are controlled in their structural features by wave action during the period of their growth.

It is to be understood that other means exit for determining porosity values. However, it has been found that acoustic velocity logs are less susceptible to error than other logs and therefore would be preferred. Radioactivity logs and electrical logs are characteristic of the latter type.

Referring now to FIGURE 4, five velocity logs are illustrated for a section known as the Endicott sandstone as encountered in one part of the State of Oklahoma. Log **10** was obtained in a first borehole A. That portion of the log covering the Endicott sandstone has been shown in detail. The log represents the incremental travel time for an acoustic wave to travel through a predetermined length or section of the sandstone bed. The log is of the type produced by systems such as disclosed in Patent No. 2,704,364 of Robert A. Broding, a co-worker of applicant. A second log **10***a* is also plotted through the same sandstone section and represents the self-potential (S.P.) curve for the same section covered by the log **10**. A similar acoustic velocity log **11** and an S.P. log **11***a* are illustrated for the borehole B. Logs **12** and **12***a* similarly were obtained in borehole C. Logs **13** and **13***a* were obtained in borehole D. Logs **14** and **14***a* were obtained in borehole E. The location of the holes is best illustrated in FIGURE 7. They span a traverse covering five townships, the area shown in FIGURE 7 being five townships long and two townships wide. In the course of carrying out the present invention, similar logs were obtained for each of the remaining boreholes appearing in FIGURE 7. However, for the purpose of the present description, detailed consideration will be given only to those logs shown in FIGURE 4.

As previously explained, the velocity logs may be employed for the purpose of determining the porosity of certain formations of interest. The system illustrated in FIGURE 6 is provided in accordance with the present invention to carry out, in analog form, the necessary treatment of data represented by the logs of FIGURE 4 to provide porosity data.

More particularly, the system of FIGURE 6 provides a record, on a first trace **20**, of a signal representative of the average porosity of the Endicott sandstone at each of the five wells. The first pulse **20***a* is representative of the average porosity in borehole A. Pulses **20***b*, **20***c*, **20***d* and **20***e* represent the average porosities in boreholes B–E, respectively.

Further, a second trace **21** is produced which represents the deviation (preferably arithmetic) of porosity from average porosity for each of the holes. The trace **21** includes pulses **21***a*–**21***e* which represent the deviation experienced or encountered at each of the boreholes A–E, respectively.

Finally, a trace **22** is produced having scalar functions recorded thereon in the form of pulses **22***a*–**22***e* representing the location of the center of gravity of the Endicott sandstone in each of the boreholes A–E, respectively.

Referring now to FIGURE 6, there is illustrated a photoelectric scanner **30** which includes a drum **31***a* for rotationally supporting a transparency **32**. A motor **33** is provided to drive the drum **31***a*. A light source **34***a* directs a beam of light to a prism **34***b* which reflects the beam of light through the transparency **32** and through a light slit in a baffle unit **35**. Light emerging from the unit **35** passes through a condensing lens **36** and impinges on a photocell **37**. The output of the photocell passes through a preamplifier **38** to a stepping switch **39** by way of channel **39***a*. The photoelectric scanner **30** is employed for the purpose of generating on channel **39***a* an electrical signal corresponding with the data on the transparency **32**. Of particular interest is that data lying within the segments **40** and **41**. Additional transparencies on drums **31***b*, **31***c* (and two additional transparencies not shown) are to be employed in the production of the data on traces **20**, **21** and **22**. Data from four additional scanners is transmitted to the switch **39** by way of channels **39***b*–**39***e*, respectively.

The arm of the stepping switch **39** is controlled by relay coil **45** which is closed momentarily at the end of alternate cycles of scanning of a given transparency. More particularly, a cam **45***a* controls a switch in circuit with battery **45***b* for periodically energizing coil **45**. The cam **45***a* is coupled to the motor **33** by a linkage **33***a*. The motor **33** also drives the additional photoelectric scanners for the transparencies on drums **31***b*, **31***c*, etc.

The arm of the stepping switch **39** is connected to a system which carries out the computations indicated by the following four equations.

$$\phi=\frac{\Delta^t \text{ log}-\Delta^t \text{ matrix}}{\Delta^t \text{ liquid}-\Delta^t \text{ matrix}} \qquad (1)$$

where:

ϕ=porosity and

Δ^t=incremental travel time for the indicated environments.

$$\bar{\phi}=\frac{\sum_1^n \phi_i}{n} \qquad (2)$$

where:

$\bar{\phi}$=average porosity,

ϕ_i=porosity at each depth along the formation, and

n=a depth function, increasing in direct proportion to depth.

$$AD=\frac{\sum_1^n |\bar{\phi}-\phi_i|}{n} \qquad (3)$$

where:

AD=arithmetic deviation and the remaining functions are as above identified with respect to Equation 2.

$$\text{C.G.}=\frac{\sum_{1}^{n} h_i \times \phi_i}{\sum_{1}^{n} \phi_i} \tag{4}$$

where:

C.G.=center of gravity of the formation, and

h_i=distance from the top of the lithologic unit being studied to the middle of the interval for which ϕ is observed.

The center of gravity (C.G.) may be expressed in feet, but can be converted to percentage by dividing the distance from the top of the formation to the center of gravity by the thickness of the unit and multiplying by 100.

In order to produce the functions represented by Equations 1–4, the signal from the arm of switch **39** is applied to a first unit which carries out operations to produce the function ϕ_i of Equation 2. It will be assumed in the following description that the formation represnted by section **40** is to be detailed and that signals will be treated only from segment **40**. The conductor **53** leading from the arm of switch **39** is connected to one input on the unit **50** which includes three sub-units **54**, **56** and **58**. Units **54** and **56** are identical units and produce an output function representative of the algebraic difference between the two functions applied to the two inputs thereof. The channel **53** leads to one input of unit **54**. The voltage on channel **53** is a varying D.C. voltage the magnitude of which corresponds with the variations in the transparency **32** as in the section **40**. A voltage source **55** is connected to the second input of both of the units **54** and **56**. The voltage from unit **55** may be a steady D.C. voltage the magnitude of which is proportional to the incremental travel time for an acoustic wave to travel through a selected earth section wherein the earth section is made up solely of the matrix (the solids) at depths of the segment **40**.

The voltage generator **57** applies to the first input of the unit **56** a steady D.C. voltage the magnitude of which is proportional to the incremental travel time of acoustic pulse through the liquid in the same formation as encountered at the depth at section **40**. The outputs of units **54** and **56** are then applied to a dividing unit **58**. Thus, there is produced at the output terminal **59***a* a voltage which is a unidirectional voltage varying in amplitude with depth. The output voltage is representative of the porosity of the formation represented by the segment **40**. The function appearing at terminal **59***a* is mathematically expressed by Equation 1.

It will be recognized that the voltages generated by units **55** and **57** will, to a considerable degree, control the magnitude of the porosity function ϕ_i appearing at terminal **59***a*. The present invention is not primarily concerned with determination of the values that are employed for the voltages from units **55** and **57**. This, in general, is fairly well-known in the art and different investigators utilize different values for the matrix and liquid velocities. therefore, specific values for such velocities will be considered given.

Terminal **59***a* is connected by conductor **60** to the arm of a multichannel stepping switch **61**. The stepping switch **61** is connected by way of linkage **33***a* to the motor **33** so that the arm of switch **61** will sweep all of the terminals of FIGURE 6 during the time interval occupied by the selected segment of interest on the transparency on drum **31***a*. For example, the arm of switch **61** will be driven successively into contact with each of its terminals during the time interval represented by the segment **40**. The linkage **33***a* is also connected to a voltage generator **63** which produces an output of stepped waveform which changes as the position of the arm of switch **61** changes. The latter two functions are employed for producing an output function on line **64** which is representative of the average porosity $\bar{\phi}$ over the section **40**. As the arm of switch **61** sweeps its contacts, there are successively stored in the storage unit **66** electrical quantities each representative of the values of the porosity ϕ_i at the various depths through section **40**.

The storage device **66** may, for example, include a plurality of circuits each of the type shown in FIGURE 6A. The voltage from terminal **59***a* is applied by switch **61** to a rectifier **70** and a resistor **71** to place a charge on a condenser **72** proportional to the magnitude of the porosity ϕ_i at one depth in section **40**. The voltage on the condenser **72** is then connected by way of a buffer device, such as a cathode follower **73**, to an adding network **74**. The sum of all of the voltages stored in unit **66** is then applied by way of channel **75** to the input of a dividing unit **76**. The voltage on channel **75** is proportional to the summation of all of the porosity values ϕ_i for the points in the segment **40** represented by the terminals on the switch **61**. This voltage is then divided in unit **76** by a voltage proportional to or representative of the number of terminals of switch **61**. The latter voltage is produced by generator **63**.

As a consequence, there is produced on the output channel **64** a voltage representative of the average porosity of the formation represented by the segment **40**. This voltage is then applied to a recorder **78** where the signal is recorded in the form of a pulse **20***a* on trace **20**.

The pulse **20***a* is recorded during the first cycle of operation of the scanner **30** and the switch **61**. Preparatory to the second cycle of the switch **61**, the switch **69**, FIGURE 6A, in each of the storage units of the unit **66** will be switched to a playback position, as in contact with terminal **69***a*, so that the successive values of ϕ_i stored in unit **66** will appear on the arm of switch **61**. Further preparatory to the second cycle, the switch **59** is moved to the lower terminal **59***b* so that the successive values of ϕ_i will be applied to conductors **80** and **81**. The values of ϕ_i produced on playback are employed to provide output functions which are respectively representative of the arithmetic deviation (AD) of porosity and the center of gravity (C.G.).

More particularly, in order to produce a physical representation of arithmetic deviation of porosity, there is provided first a subtraction unit **83** to which the average porosity function $\bar{\phi}$ on conductor **64** is applied. Subtracted from this are the successive values of ϕ_i as applied to unit **83** by way of conductor **80**. The difference between the average porosity function and the ϕ_i functions is then applied to a storage unit **84** by way of a multiterminal stepping switch **85**. Switch **85** is driven in synchronism with switch **61**, as indicated, by linkage **85***a*. The storage unit **84** is of the character of the storage unit **66** as above described. The output of the storage unit **84** is summed in a summing unit **86**. The output of the summing unit **86** is then applied to a dividing unit **87**, the denominator of which is proportional to the summation from 1 to n of ϕ minus $\bar{\phi}_i$. For this purpose the output of the generator **63** is applied as the denominator in the unit **87** as by way of the conductor **63***b*. The quotient function then appears on conductor **88** and represents the arithmetic deviation of porosity (AD). The value of the arithmetic deviation is recorded as pulse **21***a* on trace **21**.

Simultaneously with the production of the arithmetic deviation function, there is also produced a function representative of the center of gravity (C.G.). This is produced by applying to a multiplier unit **90** a voltage on conductor **81** which represents the ϕ_i values as from storage unit **66**. The product of such values and a depth function as produced by a potentiometer **91** is then applied to a multiterminal stepping switch **92**. The potentiometer **91** and switch **92** are driven in synchronism with switch **61**. A source **93** is connected across the potentiometer so that a voltage is generated which is proportional to the depth of a given ϕ_i function. The product of each ϕ_i function and its depth is then stored in a storage unit **94** of the same character as storage unit **66.** A summing unit **95** is then employed to produce on output conductor **96** a voltage which represents the summation of the products of the porosities and depths. The output conductor **96** is then connected to a dividing unit **97** as the numerator function. The denominator function is the same voltage as appears at the output of the summation unit **74.** Conductor **75** is connected by way of conductor **75***a* to the second terminal of the dividing unit **97.** The function produced on the output conductor **98** leading from the dividing unit **97** is then the center of gravity (C.G.) function for the section **40.** The conductor **98** is connected to the third input terminal of the recorder **78** to record as pulse **22***a* the center of gravity function on trace **22.** The pulses **20***a*, **21***a* and **22***a* thus represent the solutions for the formation represented by the segment **40** of the three Equations 2, 3 and 4.

The foregoing operations are then repeated for each of the transparencies on drums **31***b*, **31***c* and two additional transparencies (not shown) for the production of the pulses **20***b*, **21***b*, **22***b*, and the remaining pulses on the lower record section **40′**. The recording **40′** is a registration of new and distinctive geophysical functions descriptive of the formation as represented by the segment **40.**

Thereafter there will be produced a similar recording **41′** for the record section **41.** Pulses **20***f*–**20***j* of recording **41′** represent the average porosity for the record section **41** at each of five wells. The pulses **21***f*–**21***j* represent the deviation from average porosity. Pulses **22***f*–**22***j* represent the center of gravity functions.

The segments of sonic logs of FIGURE 4 represent the actual velocity logs for the Endicott sandstone in five wells A–E in a given section in Oklahoma. FIGURE 5 includes segments of the same logs as in FIGURE 4 but for a deeper, Tonkawa sandstone. The wells have been given the same reference characters A–E in FIGURES 4 and 5. The Endicott and Tonkawa formations have been employed in order to illustrate the application of the present invention to actual field problems. The data taken from such logs, recorded or registered in correlation with the locations of the different wells as on the record traces **20–22**, may then be employed to provide further and more revealing information as to the character of the forces which were active during the period of time that the sandstone fomations in question were being built.

More particularly, as illustrated in FIGURES 7–11, the data on the output of the recorder **78** may be employed to provide a new and informative picture of formation development and the direction which one might go from a given point of investigation to find locations more susceptible to entrapment and storage of petroleum accumulations. For example, the recorder **78** plots as scalar values the functions for each of the wells in which the logs are run. FIGURES 7–11 indicate the five different sets of functions all of which are related to the Endicott sandstone. FIGURE 7 is a srtucture contour map showing the top of the Endicott sandstone in the area in which holes A–E are located.

FIGURE 8 is an isopach map of the Endicott sandstone over the area covered by the wells A–E.

The values of trace **20***a* are plotted as to form an average porosity map such as shown in FIGURE 9. It will be noted that there are many wells from which data was gathered other than the wells A–E. As a result of the values found on trace **20**, the average porosity can be contoured to form the various contours shown in FIGURE 9.

In a similar manner, the values shown on trace **21** are plotted in FIGURE 10 and from this contours are drawn showing the arithmetic deviation from average porosity.

Finally, as illustrated in FIGURE 11, the values on trace **22** are plotted and the contours there drawn show the variations in the center of gravity for the Endicott sandstone.

While the values plotted and the contours shown may be carried out by hand, it will be recognized that automatic plotters and contouring devices may be employed for carrying out the actual construction of the maps of FIGURES 9–11.

FIGURES 12–16 comprise a similar family of maps corresponding respectively to FIGURES 7–11 but in which the data represents the Tonkawa formation. It will be noted that there are substantial differences in the contours shown and, further, it will be appreciated that only a limited area has been plotted in the maps of FIGURES 7–16. Even so, the principle of the present invention is clearly illustrated. More particularly, by striking a line such as the line X–Y across the maps of FIGURES 7–11, there may be obtained the data for plotting the five curves shown in FIGURE 17. The curve **100** represents the center of gravity of the Endicott sandstone as it occurs along the line X–Y, FIGURE 11. The line **101** represents the arithmetic deviation from average porosity along line X–Y, FIGURE 10. The curve **102** represents variations in average porosity along the line X–Y, FIGURE 9. The curves **103** and **104** respectively represent variations as taken from the isopach map of FIGURE 8 and the structure map of FIGURE 7.

The curves **100–104** correspond in essence to the five curves shown in FIGURE 1. The hypothesis upon which the FIGURES 1–3 was based may then be applied directly to the curves of FIGURE 17 to determine the nature of the forces present during the time the Endicott sandstone formation was being laid down. One can then construct additional graphs such as that of FIGURE 17 as taken along different lines to locate the areas in which there is greatest porosity and in which functions of arithmetic deviation of porosity and center of gravity will indicate the zones most likely to be reservoirs of hydrocarbon accumulations.

In FIGURE 18 there is shown a similar set of curves including curves **110**, **111**, **112**, **113** and **114** for the Tonkawa sandstone. The curves correspond with the center of gravity deviation, average porosity, isopach and structure of the Tonkawa sandstone as taken along lines P–Q of the FIGURES 12–16. Curves **110–114** correspond to those functions illustrated in FIGURES 1–3 and are to be interpreted on the basis proposed for FIGURES 1–3. The utility of the present invention is graphically shown by the use to which the newly developed data may be put, as in contours of the type shown in FIGURES 7–16.

The foregoing description has dealt primarily with the use of an analog system such as shown in FIGURE 6 for carrying out the present invention. It will be understood that the method may be practiced through use of systems other than analogs of the type above described in detail. More particularly, each operation embodied in the production of a deviation function and a center of gravity function, as well as the average porosity function, may be carried out through the use of the more flexible and versatile digital computers. The method, therefore, is not limited to the particular form of analog apparatus disclosed herein, nor to any particular analog system. Nor is the method limited to the production of the particular functions above described. Porosity may be derived from logs other than the velocity function. Even when based upon the velocity function, a different relationship may be employed other than embodied in Equation 1. Similarly, while Equation 3 specifies a deviation that is a simple arithmetic function, other deviation functions may be considered by some persons skilled in the art to present a more exact picture than the function employed herein as exemplary only. In any case, there is provided a new method of carrying out geophysical exploration. A new and interpretative set of geological data is provided which is highly useful.

The system at FIGURE 6 includes in block form a number of components which, in general, are well-known in the art and for this reason are not shown in detail. For example, the subtraction units **54**, **56** and **83** may be of the type described in Waveforms, Radiation Laboratory Series, volume 93, McGraw-Hill (1947) in the section entitled "Addition and Subtraction of Voltages and Currents," page 629. A suitable subtraction unit is described at page 642 under the heading "Cathode Coupling." Summing units are also disclosed in the same section. A suitable network is shown in Figure 18.1 at page 631 of the above reference. Dividing networks **58**, **76**, **87** and **97** may be as described in the section entitled "Multiplication and Division" in the above-identified reference. Multiplying networks such as employed in the circuit of Figure 19.1 of the above reference may be of the type disclosed in Patent 2,982,942 to J. E. White. The voltage generator **63** may be of the type described under the heading "Linear Steps of Voltage" beginning at page 617 of Waveforms which describes several types of voltage generators having stepped output functions. A trigger voltage supplied to this circuit in coincidence with each step of the switch **61** provides the synchronism for the output voltage. A direct linkage has been indicated from the relay coil **45** to the recorder drive for the recorder **78**. It is to be understood that other drive means, such as well-known Selsyn systems, may be employed to coordinate or synchronize the motion of the recorder chart with the switch **39**. Furthermore, the records **40′** and **41′** have been employed in the particular configuration shown in FIGURE 6 in order to graphically portray one form of presentation of the results of the present invention. It is to be understood that different forms of recording may be found perhaps more harmonious with the mode of end use than the form illustrated herein.

Thus, in accordance with the present invention, there is provided a new set of data relating to significant structural properties of earth formations. There is first produced a function representative of the average porosity of a given formation. Together with the foregoing function there is produced and recorded a function representative of the deviation of average porosity at various points throughout the section. Finally, there is recorded a function representative of the location of the center of gravity of a given formation. The functions are then recorded or registered in correlation with the location of the boreholes or the sites in which the various formations are encountered as on records **40′** and **41′**. From such records a new and useful interpretation is had as to the character of the formations encountered.

Having described the invention in connection with certain specific embodiments thereof, it is to be understood that further modifications may now suggest themselves to those skilled in the art and it is intended to cover such modifications as fall within the scope of the appended claims.

What is claimed is:

1. The method of determining the time-depositional changes during formation of a subterranean earth unit with respect to which variations in porosity as a function of depth within said unit are known for at least two spaced vertical lines extending through said unit, which comprises:

(a) generating a first pair of functions representative of said variations in porosity along said lines,

(b) generating a second pair of functions representative of the numerical value of the deviation from an average of said porosity functions along said lines, and

(c) registering each of said second pair of functions in correlation with the locations of said lines.

2. The method of determining time-depositional changes during formation of a subterranean earth unit with respect to which the variations in porosity as a function of depth within said unit are known for each of a plurality of spaced lines extending through said unit, which comprises:

(a) for each said line generating a function representative of the average porosity of said unit,

(b) modifying each of the average porosity functions to produce functions representative of the numerical value of the deviation from said average porosity function for each of said lines, and

(c) registering the deviation functions in correlation with the locations of said lines.

3. The method of determining the time-depositional changes during the formation of a given subterranean earth unit, which comprises:

(a) generating a first set of functions representative of a physical variable of said unit controlled primarily by variations in porosity through said unit along all of a plurality of vertical lines extending through said formation at laterally spaced points,

(b) modifying said first set of functions to produce a second set of functions representative of the product of said variations and the depth points at which they occur along each of said lines through said unit,

(c) modifying said second set of functions to produce a third set of functions representative of the quotients of said second set of functions and the summations of porosities at said depths, and

(d) registering said third set of functions in correlation with the locations of said lines.

4. The method of determining the time-depositional changes during formation of a given subterranean earth unit, which comprises:

(a) generating a first set of functions representative of a physical variable of said unit controlled primarily by variations in porosity through said unit along all of a plurality of vertical lines extending through said formation at laterally spaced points,

(b) modifying said first set of functions to produce a second set of functions representative of average porosities along said lines through said unit,

(c) establishing from said second set of functions a third set of functions representative of the numerical values of the deviations from the respective averages of the porosity over the thickness of said unit at each of said lines, and

(d) registering said third set of functions in correlation with the locations of said lines.

5. A system for well log interpretation which comprises:

(a) means to produce a first function which varies in accordance with variations in said log along a selected formation represented thereby,

(b) means for modifying said first function to produce a second function representative of the incremental formation porosity as it varies along said formation, and

(c) means responsive to said second function for generating a third function representative of the magnitude of the deviation in the porosity function from the average of said porosity function.

6. A system for well log interpretation which comprises:

(a) means to produce a first function which varies in accordance with variations in said log along a selected formation represented thereby,

(b) means for modifying said first function to produce a second function representative of the incremental formation porosity as it varies along said formation,

(c) means for generating a third function representative of the magnitude of the deviation in the porosity function from the average of said porosity function, and

(d) means for recording said third function.

7. A system for well log interpretation which comprises:

(a) means to produce a first function which varies in accordance with variations in said log along a selected formation represented thereby, and

(b) means for modifying said first function to produce a second function representative of the distance from one boundary of said formation to the location of its center of gravity.

8. A system for well log interpretation which comprises:

(a) means to produce a first function which varies in accordance with variations in said log along a selected formation represented thereby,

(b) means for modifying said first function to produce a second function representative of the distance from one boundary of said formation to the location of its center of gravity, and

(c) means for recording said second function.

9. In well logging interpretation where a function is produced which represents the magnitude of the porosity as it varies over a given formation represented on a well log, the combination which comprises:

(a) storage means for storing functions representative of the incremental porosity at each depth in a series of depth points extending across said formation,

(b) means for generating a function representative of the magnitude of the sum of said incremental porosity functions,

(c) means for producing the quotient of said sum and the number of points in said series to produce an average porosity function for said formation, and

(d) means for recording said average porosity function.

10. In a well logging interpretation where a function is produced which represents the magnitude of the porosity as it varies over a given formation represented on a well log, the combination which comprises:

(a) storage means for storing functions representative of the incremental porosity at each depth in a series of depth points extending across said formation,

(b) means for generating a function representative of the magnitude of the sum of said incremental porosity functions,

(c) means for producing the quotient of said sum and the number of points in said series to produce an average porosity function for said formation,

(d) means for storing a plurality of functions each representative of the difference between said average porosity function and said incremental porosity function at each one point in said series,

(e) means for producing a function representative of the summation of absolute magnitude of all of the difference functions for all of said depth points,

(f) means for generating a function representative of the quotient of said summation and the number of said depth points to produce a deviation function, and

(g) means for recording said deviation function.

11. In well logging interpretation where a function is produced which represents the magnitude of the porosity as it varies over a given formation represented on a well log, the combination which comprises:

(a) storage means for storing functions representative of the incremental porosity at each depth in a series of depth points extending across said formation,

(b) means for generating a function representative of the magnitude of the sum of said incremental porosity functions,

(c) means for producing the quotient of said sum and the number of points in said series to produce an average porosity function for said formation,

(d) means for recording said average porosity function,

(e) means for storing a plurality of functions each representative of the difference between said average porosity function and said incremental porosity function at each one point in said series,

(f) means for producing a function representative of the summation of absolute magnitude of all of the difference functions for all of said depth points,

(g) means for generating a function representative of the quotient of said summation and the number of said depth points to produce a deviation function, and

(h) means for recording said deviation function.

12. In well logging interpretation where a function is produced which represents the magnitude of the porosity as it varies over a given formation represented on a well log, the combination which comprises:

(a) storage means for storing functions representative of the incremental porosity at each of a plurality of depth points extending across said formation,

(b) means for reproducing the stored functions in the order of their depth occurrence,

(c) a multiplier means for producing the product of each of said stored functions and a function dependent upon the depth of the formation having the given porosity function,

(d) storage means for storing each said product,

(e) means for producing a function representative of the sum of the stored products,

(f) means for generating the quotient of the sum of the stored products divided by the sum of said porosity functions, and

(g) means for recording said quotient as representative of the center of gravity of said formation.

13. In well log interpretation where incremental porosity functions ϕ_i are known for a given formation, the method which comprises:

(a) modifying the functions ϕ_i to produce a function C.G. in accordance with the relaitonship

$$C.G.=\frac{\sum_{1}^{n} h_i \times \phi_i}{\sum_{1}^{n} \phi_i}$$

where:

C.G. is the center of gravity of the formation,

n is a depth function corresponding with each ϕ_i function and

h_i is the distance from the top of said formation to the location represented by each n function, and

(b) registering said function C.G.

14. In formation log interpretation where average porosity function $\bar{\phi}$ and incremental porosity functions ϕ_i are known for a given formation, the method which comprises:

(a) modifying the function $\bar{\phi}$ to produce a function AD in accordance with the relationship

$$AD=\frac{\sum_{1}^{n} |\bar{\phi}-\phi_i|}{n}$$

where:

AD is the arithmetic deviation,

n is a depth function for each point along said formation having a function ϕ_i, and

(b) registering said function A.D.

15. A system for indicating the time-depositional changes during formation of a subterranean earth unit with respect to which variations in a porosity dependent log as a function of depth are known for a plurality of spaced vertical bores extending through said unit which comprises:

(a) means for generating for each of said bores a first function representative of variations in porosity,

(b) means for generating for each of said bores a second function representative of the deviation from an average of said porosity along said bores, and

(c) means for registering said first and second functions at points along a space scale representative of the distance between said bores.

16. A system for indicating the time-depositional changes during formation of a subterranean earth unit with respect to which variations in a porosity dependent log as a function of depth are known for a plurality of spaced vertical bores extending through said unit which comprises:

(a) means for generating for each of said bores a first function representative of variations in porosity,

(b) means for generating for each of said bores a second function representative of the deviation from an average of said porosity along said bores,

(c) means for generating a third function representative of the distance from one boundary of said unit to the center of gravity thereof, and

(d) means for registering said first, second and third functions in correlation with the locations of said bores.

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