

Description

The present invention relates to methods and apparatus for logging earth formations penetrated by a borehole, and more particularly to methods and apparatus for compensating for borehole effects while logging such formations using nuclear means. The invention will be particularly described with respect to methods and apparatus for compensated density logging of downhole earth formations (wherein gamma rays are emitted from a logging tool into the formation and photoelectrically scattered back to the tool).

In recent years, nuclear well logs measuring the density of downhole earth formations have become increasingly important to petroleum engineers and log analysts. Density logs are a standard means for determining formation porosity. When borehole conditions are reasonable, density readings can be combined with estimates of fluid and matrix densities to yield accurate porosity values. Measurements of the photoelectric factor (P_e) have assisted lithology identification, and thereby improved the estimation of matrix density. However, previous P_e measurements have often been adversely affected by rugose boreholes and/or the pressure of barite in the drilling mud.

Porosities derived from density logs can be combined with measurements from resistivity or pulsed neutron logs to produce calculations of formation water saturations. Other combinations of density log data with that from sonic and/or neutron porosity logs can be used to determine formation lithology and to indicate formations with significant gas saturations. In certain areas even unsupplemented density log data can provide sufficient information to evaluate the formations of interest.

Density logging is based on the detection of attenuated gamma rays emitted from a radioactive source in a downhole tool. The gamma rays from the source penetrate through the toolcase, borehole, and formation. A fraction of these gamma rays are Compton scattered into and counted by one or more gamma ray detectors in the tool. The attenuation the gamma rays undergo between the source and detector(s) can, under certain conditions, be very simply related to formation bulk density. As a reasonable generalization, the count rate will decrease exponentially as the density of the formation/borehole system increases, and also as the source-detector spacing increases.

Gamma rays interact with matter principally by three processes: photoelectric absorption, pair production, and Compton scattering. Of these processes, only Compton scattering is not highly dependent upon the specific elements in the medium, depending instead upon only the density of the medium (the density being directly related to the number of electrons per unit volume). Photoelectric absorption and pair production, on the other hand, are strongly related to the atomic number Z of the nuclei in the formation and exhibit very strong gamma ray energy dependence. Therefore, current density logging tools are designed to respond primarily to Compton scattered gamma radiation, the selective response to such Compton scattered gamma radiation being achieved by proper selection of detected gamma ray energies and proper detector shielding.

Typically, present day density tools therefore measure density by observing an integrated Compton scattered gamma ray count rate over a broad, predetermined energy band. Since the higher density formation materials have higher gamma attenuation coefficients, the integrated count rate at the gamma ray detector in the logging tool will be lower when higher density material is present between the source and the detector. Using predetermined relationships, the count rates can then be converted into a measure of the formation density, and hence porosity.

In many tools, two detectors are provided and the data from both detectors are used simultaneously to provide borehole (especially mudcake) compensation. This is particularly true in compensated density logging, which uses a Cs^{137} source collimated into the formation and two collimated gamma ray detectors.

The conventional compensation concept as embodied in, for example, US—A—3864569 is based upon the idea that when a borehole attenuating factor such as mudcake is present, the count rates at both detectors will be affected. Since mudcake occupies a larger percentage of the volume sensed by the short-spaced detector, the short-spaced count rate will change more than the long-spaced count rate. This will cause the short-spaced detector to indicate an apparent density which is different from that indicated by the long-spaced detector. The difference between these apparent densities is directly proportional to the amount of correction which needs to be applied to the long-spaced density to obtain the compensated density. Such compensation concepts and methods are well known. The concepts also rely on the fact that the density measurements are made by detecting higher energy scattered gamma rays which are more penetrating and not isotropically distributed in the formation.

The addition of a photoelectric factor (P_e) measurement to density logging has proved to be quite useful in lithology identification. However, because of limited depth of investigation and strong sensitivity to elements with large atomic number, P_e measurements have been adversely affected by borehole rugosity, mudcake, washout, and barite in the drilling mud. A need therefore remains for a borehole logging method and apparatus which will give an accurate and repeatable determination of formation density, a reduction in borehole sensitivity for lithology determination, and a less borehole sensitive P_e measurement.

Briefly, according to the present invention a borehole logging method and apparatus are disclosed in which differences in the relative formation components of the signals in two detectors are minimized, and the relative borehole components are made to vary significantly. That is, in contrast to the traditional method described above, the compensation utilizes variations in the relative borehole, rather than the

formation, components. This variation can be provided in a number of different ways. For example, energy discrimination, time dependence, or mechanical means may be used. With the latter, differences in borehole response can be obtained, for example, by varying the azimuthal and/or vertical collimation aperture widths at each of two detectors.

Previously, the photoelectric factor P_e has commonly been obtained only from the longer spaced of the two density detectors. In a preferred embodiment of the present invention, a separate P_e is measured from each detector. It has been determined from test formation and well data that the short-spaced detector P_e is less sensitive to mudcake. As taught herein, this is at least in part caused by a much tighter gamma ray collimation in the short-spaced detector, coupled with the very limited penetration of the photoelectrically sensitive low energy gamma rays. Conversely, a larger collimator opening in the long-spaced detector increases the mudcake effect on the relatively shallow P_e measurement. Such P_e measurements, with different relative borehole component sensitivities, then provide a mechanism for identifying and reducing the occurrence of erroneous P_e values in zones where mudcake or washout obscures the true photoelectric properties of the formation.

It is therefore a feature of the present invention to provide an improved borehole logging method and apparatus for measuring the properties of downhole earth formations; such a method and apparatus which provide compensation for borehole effects; in which a first detector within the borehole measures radiation on a first path entering the borehole from the formation, and a first signal is then generated which is representative of the radiation so measured; in which a second detector within the borehole measures radiation of the same kind on a second path entering the borehole from the formation, and a second signal is then generated which is representative of the radiation so measured; wherein said radiation which is measured is low energy photoelectrically sensitive gamma radiation so that differences in the relative formation components of the first and second signals are minimized; and wherein in the borehole the first said path is different from the second path whereby the relative borehole components of the two signals are varied; thus enabling the borehole effects upon the two signals to be determined; and to accomplish the above features in an accurate, sensitive, versatile, and reliable method and apparatus readily suited to the widest possible use in the borehole measurement of the properties of earth formations.

Other features and advantages of the invention will be apparent from the following description.

In Figures 6, 7 and 8, non-metric units are shown, whose metric equivalents are as follows:

Measurement in inches	Metric equivalent
$\frac{1}{4}$ "	0.64 cm
$\frac{1}{2}$ "	1.27 cm
1"	2.54 cm
6"	15.24 cm
8"	20.32 cm
10"	h9L10.5025.40 cm

In order that the invention may be more fully understood, reference is made to the accompanying drawings, wherein:

Figure 1 is a figurative illustration showing one embodiment of well logging system for performing earth formation measurements in a borehole according to the present invention;

Figure 2 is a schematic representation of the relative detector responses and response components with conventional compensation methods;

Figure 3 is a schematic representation similar to Figure 2 of the relative detector responses and response components resulting from the compensation method according to the present invention;

Figure 4 is a schematic cross-sectional view taken generally on line 4—4 in Figure 1;

Figure 5 is a schematic cross-sectional view similar to Figure 4 taken generally on line 5—5 in Figure 1;

Figure 6 is a graphical illustration of test formation data showing observed lithology ratios (R) versus formation P_e ;

Figure 7 is a graphical illustration of test formation data showing observed short-spaced detector P_{es} versus formation P_e ; and

Figure 8 is a graphical illustration of test formation data showing observed long-spaced detector P_{el} versus formation P_e .

With reference to the drawings, the new and improved apparatus for measuring the density of downhole earth formations penetrated by a borehole, and the method therefor according to the present invention, will be described. Figure 1 shows schematically a well logging system suitable for performing the present invention. As shown therein, a well borehole 10 is filled with a borehole fluid 11 and penetrates the earth formations 20 to be investigated. A downhole well logging sonde 12 is suspended in the borehole 10 by means of a conventional armored logging cable 13, in a manner known in the art. Cable 13 provides for raising and lowering the sonde through the borehole and contains one or more electrical conductors 16 for communicating between the sonde 12 and a surface electronics package 17, as desired.

EP 0 206 593 B1

A sheave wheel 14 at the surface, over which cable 13 passes, is electrically or mechanically coupled, as indicated by dotted line 15, to a well logging recorder 18. Recorder 18 may comprise an optical recorder or magnetic tape, or both, as known in the art, for recording the measurements made by the downhole sonde 12 as a function of the depth in the borehole of the sonde 12.

In the downhole sonde 12, a gamma ray source 21, such as a 1.5 curie Cs¹³⁷ source (emitting gamma rays having initial energies of 0.66 MeV), is separated from near and far gamma ray detectors 22 and 23, respectively, by a suitable tungsten gamma ray shield and pad housing 24. Shield 24 shields the detectors 22 and 23, in part, from gamma rays emitted directly toward them from the gamma ray source 21. Detectors 22 and 23, which have spectral capabilities and are preferably NaI(Tl) crystals with low noise photomultiplier tubes, are connected in turn to control and telemetry electronics unit 25 which controls and powers the detectors, receives count rate and energy information therefrom, and telemeters information measured by the detectors to the surface by means of the logging cable 13.

A skid 28 decentralizes the sonde 12 in borehole 10 and holds the sonde tightly against the wall of the borehole, to reduce mudcake and washout effects. The mudcake and washout effects, however, are not entirely eliminated in most cases. Therefore, as discussed above, many dual detector nuclear logging systems commonly employ borehole compensation using data from both detectors simultaneously. This is particularly true in compensated density logging as shown in Figure 1.

As with other density logging tools, the present invention measures density from the attenuation of gamma rays traversing the formation 20 between the source 21 and detectors 22 and 23. A reduction in the number of observed gamma rays implies an increase in formation density. For energies above about 125 KeV, in most formations the attenuation is caused by Compton scattering with electrons. Therefore, tool response is related to formation electron density (ρ_e) rather than actual bulk density (ρ_b):

$$(1) \quad \rho_e = \frac{2\bar{Z}}{\bar{A}} \rho_b$$

where $\bar{Z}$ and $\bar{A}$ are average atomic number and atomic weight of the formation, respectively.

By convention, density tools are normally calibrated to match the bulk density of water-saturated limestone rather than electron density. The measured apparent density (ρ_a) from sonde 12 is thereby related to electron density by:

$$(2) \quad \rho_a = 1.0704 \rho_e - 0.1883$$

Using this procedure, it is assumed that $\rho_b = \rho_a$ for water-filled limestone and this is also a good approximation for liquid-saturated sand and dolomite. However, a correction is required to obtain ρ_b for materials such as anhydrite, gypsum, halite, sylvite and gas bearing formations.

Below 125 KeV another attenuation mechanism, photoelectric absorption, becomes significant. In general, the photoelectric absorption cross section (probability) is related to two variables: the gamma ray energy (E), and the atomic number (Z) of the material through which the gamma ray is passing:

$$\text{photoelectric absorption} \sim Z^{4.6}/E^3$$

This expression states that: (1) photoelectric absorption is important only at low energies, and (2) the amount of absorption is strongly related to the atomic number of the elements or materials involved. If an energy range is selected below 125 KeV which is sensitive to photoelectric absorption, then the observed count rate in this low energy range will fluctuate with changes in Z as well as with changes in formation density. Normalization, via a ratio, to the count rate in a higher energy range which is affected by density changes, but not Z changes, will result in a parameter which is sensitive to photoelectric absorption effects alone. Such a ratio can be converted via predetermined test formation relationships into a measurement of P_e , the photoelectric factor of the formation. P_e is defined by the following:

$$(3) \quad P_e = (Z_e/10)^{3.6}$$

where Z_e is the effective atomic number of the formation. For individual elements $Z_e = Z$. For mixtures, Z_e is a weighted combination of the atomic numbers of the elements in the mixture. Z_e , and hence P_e , are strongly influenced by the highest atomic number element present. For this reason P_e is functionally related to lithology type, since silicon, calcium, and magnesium (in sand, lime, and dolomite) have significantly different atomic numbers. General applications for P_e measurements for density logging tools, and details of the general underlying physics associated with the measurement, are well known in the art.

Summarizing and applying the above discussion more specifically, and with reference to Figure 1, it will now be seen that the density compensation principle is based upon the fact that the relative attenuation from the borehole (principally caused by the mudcake or washout) and from the formation along path S→A→D22 (from "S" (source 21), to point A, to D22 (detector 22)) is different from that along path S→B→D23. The entire source-to-detector spacing is involved in the formation signals because of the more

penetrating nature of the higher energy gamma rays which are detected. The borehole components along each of these paths are roughly the same, since the detected higher energy gamma rays from the formation tend to retain the collimation features induced by the source. However, a much larger formation component exists along path S→B→D23. The relative detector responses R(D22) and R(D23) can be visualized as depicted in Figure 2, where the respective borehole components BH are equal, but the formation components FM differ as described.

Hence, in a given formation, a change in mudcake thickness will cause a bigger fractional change in the response in detector 22. The formation response with no mudcake, as described earlier, is represented mathematically by:

$$(4) \quad R(FM) = f(R(D1), R(D2)).$$

As is well known, the compensation is then spatially achieved by causing the relative formation response to vary while holding the borehole response constant.

According to the present invention, borehole compensation can be based around the entirely different principle of minimizing differences in the formation components of the signals in two detectors, while varying the relative borehole components significantly. Schematically, this is represented in Figure 3, where the respective formation components FM are equal, but the borehole components BH differ. As in conventional compensation methods, the true formation response R(FM) is given by:

$$(5) \quad R(FM) = f'(R(D1), R(D2)).$$

The key difference is that the compensation mechanism is based around variation in the relative borehole, rather than the formation, components. The borehole component can be varied by any appropriate means, as desired, such as energy discrimination, time dependence, mechanical means, and so forth (optimizing, of course, for the particular variable which is to be measured).

In a preferred embodiment, the present invention lends itself well to the photoelectrically sensitive lithology (P_e) measurement from a compensated density tool such as tool 12, using mechanical means to achieve variations in the borehole component. The low energy scattered gamma rays comprising the photoelectric (not the Compton) source distribution for signals measured in detectors 22 and 23 of the tool may be seen to be originating in a small volume of the formation immediately adjacent to each detector, since these low energy gamma rays have a very limited range in earth formations. As described more particularly by Bertozzi, Ellis, and Wahl (Bertozzi, W., Ellis, D. V., and Wahl, J. S. "The Physical Foundation of Formation Lithology Logging with Gamma Rays", Geophysics, Vol. 46, No. 10 (October, 1981), pp. 1439—1455), this source is generally within about 2—3 cm. of the tool housing and is roughly isotropically distributed. Hence the photoelectric "source"-to-detector spacing is approximately the same for each detector, and hence the FM components in Figure 3 are approximately the same.

In the present invention, the physical location and the energy of the Cs^{137} source 21 in the tool in fact have little to do with the effective source of the shallow P_e measurement. This fact is also evidenced in that P_e can similarly be measured using natural gamma rays from K-U-Th in the formation. (On this point see Smith, H. D., Jr., Robbins, C. A., Arnold, D. M., Gadeken, L. L., and Deaton, J. G., "A Multi-Function Compensated Spectral Natural Gamma Ray Logging System", paper SPE 12050 presented at the SPE 58th Annual Technical Conference and Exhibition, San Francisco, October 5—8, 1983.)

Since the formation path lengths in this case are similar, mechanical means may be used in the lithology measurement to vary the relative borehole path lengths into the two detectors. When varied significantly, compensation for the borehole effects can then be achieved according to the present invention. Thus, in a preferred embodiment, differences in borehole response are obtained by varying the azimuthal and/or vertical aperture width at the two (or more) detectors, rather than by creating variations in the source-to-detector spacing.

Figures 4 and 5 show such a variation in the detector aperture widths. Detectors 22 and 23 are surrounded by respective portions 42 and 43 of shielding 24. Respective beryllium "windows" or apertures 52 and 53 have been inserted into the shielding 24. A similar beryllium window 54 (Figure 1) is provided over the source 21. The beryllium windows 52 and 53 over the detectors improve the transmission of scattered gamma rays into the housing from the formation, particularly low energy photons that are required for determining P_e . The beryllium window 54 over source 21 enables a greater number of properly collimated high energy gamma rays to enter the formation 20.

Detector 23 (Figure 4) has a relatively large opening 53, resulting in radiation collimation with a large azimuthal opening angle (β). Detector 22 has a considerably smaller opening angle (α) in its aperture 52 through its shielding 42. As can be clearly seen from Figures 4 and 5, therefore, detector 23 receives a larger fraction of radiation transmitted through the mud and mudcake 55 than detector 22, especially when non-radial paths are considered.

In the preferred embodiment, if the short-spaced detector is designed like detector 22, and the long-spaced detector like detector 23, then compensation is preferably achieved using detector 22 for the primary measurement, since it will be less sensitive to borehole effects. Experiments verifying the principles of the present invention have shown that angular effects dominate over the Cs^{137} source-to-

detector spacing for the P_s measurement. In fact, the short-spaced detector with a narrow collimation slot requires only about half as much P_s correction for non-barite mudcake or standoff compared to the long-spaced detector with a larger azimuthal and vertical aperture. Therefore, the preferred embodiment provides borehole compensation for the short-spaced P_{ss} using the borehole related difference between the two P_s measurements P_{ss} (short-spaced) and P_{sl} (long-spaced), as described above.

The increased photoelectric attenuation at lower energies in higher P_s formations, such as limestone, is most effectively measured with a lithology ratio, R , of counts in a "hard" Compton dominated high energy range to those in a "soft" photoelectrically sensitive lower energy range. The presently preferred energy ranges have been determined from analysis of spectral data to obtain maximum photoelectric signal to noise sensitivity. In the present invention, the preferred hard range is about 120–500 KeV, and the soft about 40–90 KeV.

Detectors 22 and 23 yield lithology ratios, R_s and R_L , respectively, which can be converted into P_s values using relationships derived in known P_s formations. Figure 6 illustrates R_s and R_L versus known P_s for selected sand, dolomite, and limestone test formations, with fresh water boreholes and no mudcake or standoff. Data are shown for both 15.24 and 25.4 cm 6 and 10 inch diameter boreholes in the limestone formations. Several things are apparent from the Figure. First, the R to P_s conversion relation is almost linear in each detector, and both R_L and R_s have similar dynamic ranges. Also, for formation of given P_s , a consistently higher ratio is observed in the short-spaced detector. This is caused by the different collimation apertures of the two detectors, and also because the short-spaced detector is more likely to observe single Compton scattered events than the long-spaced detector.

These effects induce slight differences in the spectral shapes from the two detectors, and hence different R values are observed. The tighter short-spaced detector collimation can also induce a slight density based sensitivity in R_s (not significant in Figure 6). Another feature, apparent from the 15.24 and 25.4 cm 6 and 10 inch borehole data, is that there is a larger borehole (size) sensitivity in R_L than R_s . This effect, mentioned above, will now be amplified further.

Since it is possible to make independent P_s measurements in each detector, it would at first appear tempting to compensate the long-spaced P_s using the short-spaced P_s in a manner analogous to the well-known compensated density measurement. As is now clear, however, there are significant differences in the density and P_s measurement concepts. The entire source-to-detector spacing enters into the density measurement, in large part due to the more penetrating nature of the higher energy gamma rays observed. Hence, the effective formation pathlengths contributing to the density measurement are considerably different in the two detectors due to the different spacings. In addition, the more energetic gamma rays are highly directional. These factors tend to maximize the differences in the formation signals (pathlengths) observed. At the same time, differences in the borehole components in each detector in the density measurement are minimized since the collimated gammas tend to traverse similar borehole pathlengths between the source 21 and each of the detectors 22 and 23. The net result is a change in the relative borehole to formation component signals at the two spacings, which leads to the compensated density measurement discussed earlier.

The photoelectric signal, however, is very short range (on the order of 2.54 cm (one inch)). Therefore, the effective photoelectric "source" is located in the formation approximately opposite each detector. Hence, unlike the principle involved in density measurements, the formation pathlengths contributing to the photoelectrical signals in both detectors are similar, and the source-to-detector spacing in the tool itself is not important. Neither is the source energy, since, as also mentioned earlier, it has been shown that a similar photoelectric measurement can be made using the natural gamma sources in the formation.

Pathlength independence is not true of the borehole components of the photoelectric signals in the two detectors, however (particularly in non-barite boreholes). The solid angle of the collimation aperture from the formation into each detector controls the relative photoelectric borehole sensitivity in that detector. A wider aperture permits longer gamma ray pathlengths in the borehole medium (mudcake or mud) prior to detection, and hence more borehole dependence. This effect is enhanced by the isotropic nature of the formation photoelectric gamma "source", which emphasizes (longer) non-radial borehole path lengths into less collimated detectors. A tightly collimated detector, conversely, accentuates the measurement of radial (straight-in) gamma rays, which have shorter average borehole pathlengths.

The net result of these effects is that the tightly collimated short-spaced P_{ss} measurement of detector 22, particularly in non-barite muds, has a smaller relative borehole component, and is less sensitive to borehole rugosity, standoff, and mudcake, than is the long-spaced P_{sl} measurement of detector 23. This directly contrasts with compensated density measurements in which the short-spaced detector is more borehole sensitive. The increased relative P_{sl} borehole sensitivity is illustrated in the 15.24 and 25.4 cm (6" and 10") borehole limestone data in Figure 6. It is also shown in Figures 7 and 8, which depict known P_s values in sand, limestone and dolomite test formations versus apparent P_{ss} and P_{sl} values measured by the present invention. A variety of borehole conditions is shown. Standoff data refers to tool standoff from the borehole wall in fresh water; mudcake data includes both barite (2%, 8%, 20%) and non-barite (47% Al_2O_3) simulated cakes interposed between the tool and the formation.

Note in the short-spaced P_{ss} data in Figure 7 that all the standoffs and non-barite mudcakes induce smaller deviations from the nominal calibration curve than the corresponding materials adjacent to the long-spaced detector (Figure 8). This is especially true in the limestone formation where the contrast

between borehole P_o and formation P_o is greatest. As an illustration, a 1.27 cm 0.5-inch-thick non-barite mudcake between the tool pad and a $P_o=4.85$ limestone causes the long-spaced detector to read an apparent $P_{oL}=3.85$. The short-spaced detector obtains an apparent $P_{oS}=4.3$, only about half as much in error. A 2.54 cm one-inch water standoff (which could easily be caused downhole by borehole rugosity or washouts) in the same $P_o=4.85$ formation causes an apparent $P_{oL}=2.6$ and $P_{oS}=3.7$, again only about one half the error in the short-spaced detector.

Barite mudcakes, and in particular when there is more than just a few percent barite present, cause both detectors to indicate much too high P_o values in all formations, since barium has a very high P_o . There is still, however, a significant formation P_o sensitivity, as evidenced by the slopes of the curves in Figures 7 and 8, even with as much as 1.27 cm 0.5 in of 20% barite mudcake present. There is also a slight difference in P_o barite sensitivity in the two detectors. However, field experience has indicated that small systematic errors (such as tool skew, rotation, or differential standoff) can override these differences. In barite boreholes, therefore, P_o differences can be indicative of mudcake, washout, slightly differential standoff, or tool skew. In general, both P_o values in all these situations will be too high.

In non-barite muds where the two P_o values are in agreement, it is likely that both detectors are reading the true formation P_o . Where the two P_o values differ, the presence of mudcake or washout is indicated. In such zones both P_o values are probably low, with P_{oS} closer to the true formation value since it is less influenced by the intervening non-barite material.

Observable photoelectric absorption of low energy scattered gamma rays in downhole formations takes place regardless of the origin of the gamma radiation. Neutron induced secondary gamma sources in formations give rise to photoelectric absorption reactions, but a large number of secondary gamma sources are also generated in the borehole fluid, casing, and/or cement. These induced borehole gamma rays are detected without having undergone photoelectric absorption in the formation, and hence strongly mask the formation photoelectric signature. Density tool gamma sources on the other hand, such as source 21, are collimated into the formation, as are the detectors 22 and 23. This minimizes borehole interference and makes formation photoelectric absorption measurements possible. Since natural gamma sources are located in the formation in the first place (casing, cement, and most borehole fluids are relatively inert), natural gamma spectroscopy also lends itself to the measurement of formation photoelectric absorption. Natural gamma based photoelectric measurements are more borehole sensitive than density tool based measurements, however, because the detectors in such tools are not usually collimated into the formation.

As may be seen, therefore, the present invention has numerous advantages. Since P_o measurements made with density logging tools having a very limited depth of investigation, it is desirable to have a direct indication of borehole induced errors in the observed P_o values. The method and apparatus according to the present invention have been designed to provide this formation, along with accurate and repeatable compensated density and P_o measurements. Photoelectric ratio measurements made in each detector 22 and 23 are independently converted into P_{oS} and P_{oL} values, respectively. Extensive test formation and field log data in both barite and non-barite boreholes have been analyzed, and comparisons of the results from the present invention with natural gamma spectroscopy derived photoelectric logs have been made. These data confirm that due to collimation differences, long-spaced detector P_o measurements are more influenced by borehole conditions than short-spaced detector P_o measurements.

The present invention is extremely versatile, and lends itself well to other measurements, such as neutron porosity. Two density measurements can be made at the same detector spacing above and below the source, but with different azimuthal and/or vertical apertures. The spacing and aperture compensation concepts can also be combined, with the short-spaced detector having the larger aperture, so that it is more sensitive to the borehole. Energy dependence can even be employed, since in a density measurement the scattered gamma rays from near the borehole tend to be higher in energy. The invention thus furnishes a new and powerful borehole compensation method and apparatus which are readily suited to the widest use in the borehole measurement of earth formation properties.

While the methods and forms of apparatus herein described constitute preferred embodiments of this invention, it is to be understood that the invention is not limited to these precise methods and forms of apparatus.

Claims

1. A method of compensating for borehole effects in logging downhole earth formations, which method comprises:

(a) measuring, with a first detector within the borehole, radiation on a first path entering the borehole from the formation, and generating a first signal representative of the radiation so measured,

(b) measuring, with a second detector within the borehole, radiation of the same kind on a second path entering the borehole from the formation, and generating a second signal representative of the radiation so measured,

(c) determining, from said signals, the borehole effects thereon; characterised in that said radiation which is measured is low energy photoelectrically sensitive gamma radiation so that differences in the relative formation components of the first and second signals are minimized; and wherein, in the borehole, the first said path is different from the second path whereby the relative borehole components of the two

between borehole P_o and formation P_o is greatest. As an illustration, a 1.27 cm 0.5-inch-thick non-barite mudcake between the tool pad and a $P_o=4.85$ limestone causes the long-spaced detector to read an apparent $P_{oL}=3.85$. The short-spaced detector obtains an apparent $P_{oS}=4.3$, only about half as much in error. A 2.54 cm one-inch water standoff (which could easily be caused downhole by borehole rugosity or washouts) in the same $P_o=4.85$ formation causes an apparent $P_{oL}=2.6$ and $P_{oS}=3.7$, again only about one half the error in the short-spaced detector.

Barite mudcakes, and in particular when there is more than just a few percent barite present, cause both detectors to indicate much too high P_o values in all formations, since barium has a very high P_o . There is still, however, a significant formation P_o sensitivity, as evidenced by the slopes of the curves in Figures 7 and 8, even with as much as 1.27 cm 0.5 in of 20% barite mudcake present. There is also a slight difference in P_o barite sensitivity in the two detectors. However, field experience has indicated that small systematic errors (such as tool skew, rotation, or differential standoff) can override these differences. In barite boreholes, therefore, P_o differences can be indicative of mudcake, washout, slightly differential standoff, or tool skew. In general, both P_o values in all these situations will be too high.

In non-barite muds where the two P_o values are in agreement, it is likely that both detectors are reading the true formation P_o . Where the two P_o values differ, the presence of mudcake or washout is indicated. In such zones both P_o values are probably low, with P_{oS} closer to the true formation value since it is less influenced by the intervening non-barite material.

Observable photoelectric absorption of low energy scattered gamma rays in downhole formations takes place regardless of the origin of the gamma radiation. Neutron induced secondary gamma sources in formations give rise to photoelectric absorption reactions, but a large number of secondary gamma sources are also generated in the borehole fluid, casing, and/or cement. These induced borehole gamma rays are detected without having undergone photoelectric absorption in the formation, and hence strongly mask the formation photoelectric signature. Density tool gamma sources on the other hand, such as source 21, are collimated into the formation, as are the detectors 22 and 23. This minimizes borehole interference and makes formation photoelectric absorption measurements possible. Since natural gamma sources are located in the formation in the first place (casing, cement, and most borehole fluids are relatively inert), natural gamma spectroscopy also lends itself to the measurement of formation photoelectric absorption. Natural gamma based photoelectric measurements are more borehole sensitive than density tool based measurements, however, because the detectors in such tools are not usually collimated into the formation.

As may be seen, therefore, the present invention has numerous advantages. Since P_o measurements made with density logging tools having a very limited depth of investigation, it is desirable to have a direct indication of borehole induced errors in the observed P_o values. The method and apparatus according to the present invention have been designed to provide this formation, along with accurate and repeatable compensated density and P_o measurements. Photoelectric ratio measurements made in each detector 22 and 23 are independently converted into P_{oS} and P_{oL} values, respectively. Extensive test formation and field log data in both barite and non-barite boreholes have been analyzed, and comparisons of the results from the present invention with natural gamma spectroscopy derived photoelectric logs have been made. These data confirm that due to collimation differences, long-spaced detector P_o measurements are more influenced by borehole conditions than short-spaced detector P_o measurements.

The present invention is extremely versatile, and lends itself well to other measurements, such as neutron porosity. Two density measurements can be made at the same detector spacing above and below the source, but with different azimuthal and/or vertical apertures. The spacing and aperture compensation concepts can also be combined, with the short-spaced detector having the larger aperture, so that it is more sensitive to the borehole. Energy dependence can even be employed, since in a density measurement the scattered gamma rays from near the borehole tend to be higher in energy. The invention thus furnishes a new and powerful borehole compensation method and apparatus which are readily suited to the widest use in the borehole measurement of earth formation properties.

While the methods and forms of apparatus herein described constitute preferred embodiments of this invention, it is to be understood that the invention is not limited to these precise methods and forms of apparatus.

Claims

1. A method of compensating for borehole effects in logging downhole earth formations, which method comprises:

(a) measuring, with a first detector within the borehole, radiation on a first path entering the borehole from the formation, and generating a first signal representative of the radiation so measured,

(b) measuring, with a second detector within the borehole, radiation of the same kind on a second path entering the borehole from the formation, and generating a second signal representative of the radiation so measured,

(c) determining, from said signals, the borehole effects thereon; characterised in that said radiation which is measured is low energy photoelectrically sensitive gamma radiation so that differences in the relative formation components of the first and second signals are minimized; and wherein, in the borehole, the first said path is different from the second path whereby the relative borehole components of the two



signals are different, thus enabling the borehole effects on the two signals to be determined.

2. A method according to claim 1, wherein said steps of measuring low energy gamma radiation each further comprise detecting low energy scattered gamma radiation having a substantially isotropic distribution substantially equivalent to a photoelectric source located in a volume of the formation substantially adjacent the respective said detector.

3. A method according to claim 1 or 2, further comprising physically varying the relative borehole path lengths along the first and second paths, while the effective formation signals for the first and second detectors remain substantially the same.

4. A method according to claim 3, wherein said step of physically varying the relative borehole path lengths along the first and second paths further comprises measuring the radiations using different effective aperture widths in the detectors.

5. A method according to any of claims 1 to 6, further comprising deriving from said signals a measure of the photoelectric absorption properties of the formation.

6. Apparatus for logging downhole earth formations penetrated by a borehole and compensating for borehole effects, comprising:

a) a first detector (22) for measuring within the borehole radiation on a first path entering the borehole from the formation, and generating a first signal representative of the radiation so measured,

b) a second detector (23) for measuring within the borehole radiation on a second path of the same kind entering the borehole from the formation, and generating a second signal representative of the radiation so measured,

c) means (17, 25) for determining, as a predetermined function of said signals, the borehole effects thereon; characterised in that said detectors are arranged to detect low energy photoelectrically sensitive scattered gamma radiation so that differences in the relative formation components of the first and second signals are minimized; and wherein the detectors are so arranged that, in the borehole, the first path is different from the second path whereby the relative borehole components of the two signals are different.

Patentansprüche

1. Verfahren zum Kompensieren von Bohrlocheinflüssen bei der Vermessung von unten im Bohrloch befindlichen Erdformationen, welches Verfahren umfaßt:

(a) Messen der Strahlung auf einem ersten von der Formation in das Bohrloch eintretenden Weg mit einem ersten Detektor innerhalb des Bohrlochs und Erzeugen eines ersten Signals, das die so gemessene Strahlung darstellt,

(b) Messen der Strahlung gleicher Art auf einem zweiten von der Formation in das Bohrloch eintretenden Weg mit einem zweiten Detektor innerhalb des Bohrlochs und Erzeugen eines zweiten Signals, das die so gemessene Strahlung darstellt,

(c) Bestimmen der Bohrlocheinflüsse auf diese Strahlung aus den besagten Signalen; dadurch gekennzeichnet,

daß die gemessene Strahlung photoelektrisch empfindliche Gammastrahlung von geringer Energie ist, so daß Unterschiede in den relativen Formationskomponenten des ersten und des zweiten Signals minimiert werden;

und bei welchem in dem Bohrloch der erste Weg sich von dem zweiten Weg unterscheidet, wodurch die relativen Bohrlochkomponenten der beiden Signale verschieden sind und somit eine Bestimmung der Bohrlocheinflüsse auf die beiden Signale ermöglichen.

2. Verfahren nach Anspruch 1, in welchem die besagten Schritte der Messung von Gammastrahlung von geringer Energie jeweils weiterhin enthalten das Erfassen von diffuser Gammastrahlung von geringer Energie mit einer im wesentlichen isotropischen Verteilung, die im wesentlichen einer photoelektrischen Quelle entspricht, welche in einem Volumen der Formation im wesentlichen neben dem jeweiligen besagten Detektor liegt.

3. Verfahren nach Anspruch 1 oder 2, weiterhin enthaltend das physikalische Verändern der relativen Bohrlochweglänge entlang des ersten und des zweiten Weges, während die wirksamen Formationssignale für den ersten und den zweiten Detektor im wesentlichen gleich bleiben.

4. Verfahren nach Anspruch 3, in welchem der Schritt des physikalischen Veränderns der relativen Bohrlochweglänge entlang des ersten und des zweiten Weges weiterhin enthält das Messen der Strahlungen unter Verwendung unterschiedlicher wirksamer Aperturweiten in den Detektoren.

5. Verfahren nach einem der Ansprüche 1 bis 6, weiterhin enthaltend das Ableiten eines Maßes für die photoelektrischen Absorptionseigenschaften der Formation aus den besagten Signalen.

6. Gerät zum Vermessen von unten im Bohrloch befindlichen Erdformationen, durch welche ein Bohrloch verläuft, und zum Kompensieren von Bohrlocheinflüssen, enthaltend:

(a) einen ersten Detektor (22) zum Messen der Strahlung auf einem ersten Weg, der von der Formation in das Bohrloch eintritt, innerhalb des Bohrlochs und zum Erzeugen eines ersten Signals, welches die so gemessene Strahlung darstellt,

(b) einen zweiten Detektor (23) zum Messen der Strahlung auf einem zweiten Weg, der von der Formation in das Bohrloch eintritt, innerhalb des Bohrlochs und zum Erzeugen eines zweiten Signals, welches die so gemessene Strahlung darstellt,



(c) Mittel (17, 15) zur Bestimmung der Bohrlocheinflüsse auf diese Strahlung als vorbestimmte Funktion der besagten Strahlung; dadurch gekennzeichnet,

daß die besagten Detektoren so angeordnet sind, daß sie photoelektrisch empfindliche, diffuse Gammastrahlung von geringer Energie aufnehmen, so daß Unterschiede in den relativen Formationskomponenten des ersten und des zweiten Signals minimiert werden;

und in welchem die Detektoren so angeordnet sind, daß in dem Bohrloch der erste Weg sich von dem zweiten Weg unterscheidet, wodurch die relativen Bohrlochkomponenten der beiden Signale unterschieden sind.

10 Revendications

1. Procédé de compensation des effets du sondage dans la diagraphie des formations terrestres en fond de sondage, ledit procédé comprenant:

a) la mesure, avec un premier détecteur placé dans le sondage, d'un rayonnement suivant un premier trajet pénétrant dans le sondage à partir de la formation, et la création d'un premier signal représentatif du rayonnement ainsi mesuré,

b) la mesure, avec un second détecteur placé dans le sondage, d'un rayonnement de même type suivant un second trajet pénétrant dans le sondage à partir de la formation, et la création d'un second signal représentatif du rayonnement ainsi mesuré,

c) la détermination, à partir des signaux, des effets du sondage sur ces signaux, caractérisé en ce que le rayonnement qui est mesuré est un rayonnement gamma sensible photoélectriquement et de faible énergie, de sorte que les différences des composantes relatives dues aux formations du premier et du second signal soit réduites au minimum, et en ce que, dans le sondage, le premier trajet diffère du second trajet, si bien que les composantes relatives des deux signaux qui sont dues au sondage sont différentes, permettant ainsi la détermination des effets du sondage sur les deux signaux.

2. Procédé selon la revendication 1, dans lequel les étapes de mesure d'un rayonnement gamma de faible énergie comprennent en outre, chacune, la détection d'un rayonnement gamma diffusé de faible énergie ayant une distribution pratiquement isotrope qui équivaut pratiquement à une source photoélectrique placée dans un volume de la formation sensiblement adjacent au détecteur respectif.

3. Procédé selon la revendication 1 ou 2, dans lequel, en outre, on fait varier physiquement les longueurs relatives des trajets par rapport au sondage le long du premier et du second trajets, alors que les signaux efficaces relatifs à la formation restent pratiquement les mêmes pour le premier et le second détecteurs.

4. Procédé selon la revendication 3, dans lequel l'étape de variation physique des longueurs relatives des trajets par rapport au sondage le long du premier et du second trajets comporte en outre la mesure des rayonnements avec des largeurs efficaces différentes d'ouvertures dans les détecteurs.

5. Procédé selon l'une quelconque des revendications 1 à 4, comprenant en outre la déduction, à partir desdits signaux, d'une mesure des propriétés d'absorption photoélectrique de la formation.

6. Appareil de diagraphie de formations terrestres en fond de sondage, ces formations étant traversées par un sondage, et de compensation des effets du sondage, comprenant:

a) un premier détecteur (22) destiné à mesurer, à l'intérieur du sondage, un rayonnement pénétrant dans le sondage à partir de la formation suivant un premier trajet, et à créer un premier signal représentatif du rayonnement ainsi mesuré,

b) un second détecteur (23) destiné à mesurer, à l'intérieur du sondage, un rayonnement de même type entrant dans le sondage à partir de la formation suivant un second trajet, et à créer un second signal représentatif du rayonnement ainsi mesuré,

c) des moyens (17, 25) destinés à déterminer, sous forme d'une fonction prédéterminée de ces signaux, les effets du sondage sur ces signaux,

caractérisé en ce que les détecteurs sont agencés pour détecter un rayonnement gamma diffusé sensible photoélectriquement et de faible énergie de façon que les différences des composantes relatives du premier et du second signaux dues à la formation, soient réduites au minimum, et en ce que les détecteurs sont disposés de manière que, dans le sondage, le premier trajet soit différent du second trajet, si bien que les composantes relatives des deux signaux qui sont dues au sondage sont différentes.

