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(54) **Title:** METHOD FOR ESTIMATING ROCK PETROPHYSICAL PARAMETERS USING TEMPERATURE MODIFIED NMR DATA

(57) **Abstract:** Carbonate formations yield unreliable, down hole NMR results. Inter alia, these results must be corrected for temperature. The invention features several methods for obtaining more reliable NMR results for rock petrophysical parameters in carbonate rock formations based upon adjusting T^2 data with respect to temperature.

METHOD FOR ESTIMATING ROCK PETROPHYSICAL PARAMETERS
USING TEMPERATURE MODIFIED NMR DATA

Field of the Invention:

The invention relates to a method for estimating rock petrophysical parameters of underground rock formations in oil and gas wells and, more particularly, to a process for utilizing temperature modified NMR data that yields more accurate petrophysical interpretations in carbonate rocks.

BACKGROUND OF THE INVENTION

Nuclear Magnetic Resonance (NMR) as a well logging technique does not always yield useful results. Part of the problem with NMR logging is a consequence of faulty assumptions, particularly as they apply to carbonate rocks. Carbonates are particularly troublesome because great variations in their pore sizes and organic materials distributed throughout the grains can cause misleading results. Conventional interpretation of NMR measurements is based on a number of potentially faulty assumptions, to wit:

1) In addition to the bulk relaxation mechanism, magnetization decays because water molecules diffuse to the surface of the grain where they experience an enhanced relaxation rate. This is assumed to be a result of their interaction with local magnetic fields associated with paramagnetic impurities in the grain.

2) The pore space is divided into separate pores that do not interact with each other.

3) Within each pore, magnetization is assumed to be uniform. The basis for the latter assumption is that

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$pV_s/D \ll 1$, where D is the diffusion coefficient in the bulk fluid, V_s is the volume to surface ratio of the pore, and p is the surface relaxivity. The characteristic decay time constant of spin-spin relaxation of any pore is then given as:

$$1/T_2 = p/V_s + 1/T_{2b} \qquad (1)$$

where T_{2b} is the bulk relaxation time.

4)   The magnetization decay can be represented as an integral of contributions of all such components due to the multitude of pores of different volume to surface ratio. If the probability density function of T_2 is $g(T_2)$, this integral can then be resolved into the components represented by $g(T_2)$ by a number of established fitting procedures. In practice, $g(T_2)$ is widely considered to represent the pore size distribution.

The above assumptions are flawed in general, and particularly several of them do not hold for carbonate rocks. The measured decay is not readily translatable to pore sizes. (Assumption 4). Inverted T_2 distributions in grain-supported carbonates are unimodal, whereas petrography studies show them to be at least bimodal. Petrographs show that the grains are composed of micrite particles, which form the intragranular porosity. The juxtapositioning of pores of diverse sizes, and the diffusion of magnetic moments among these pores, causes the breakdown of the relationship between T_2 and pore size. (Assumption 3).

Most recently, we have discovered that NMR tests performed on carbonate rock samples from Middle East oil wells are temperature dependent. The temperature dependencies are contrary to established beliefs for NMR response in fluid-saturated rocks. The prior art was based

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on the supposition that there were no significant temperature
dependencies for the NMR response. Closer examination of
this work suggests that these conclusions were valid only for
sandstone media. Data obtained for carbonate media were
simply inconsistent. Furthermore, a recent comparison of
laboratory core data with data obtained from logs taken in
the Middle East wells also shows inconsistencies.

The studies made in accordance with the present
invention confirm the prior art conclusion with respect to a
limited number of sandstone media. That is, the change in
response to temperature is weak or non-existent. However,
core samples taken from the Middle East wells cited in the
comparative data show a dependence on temperature which is
consistent with the observed discrepancies between laboratory
core data and log data.

The extent of the temperature dependence is very
significant for NMR logging interpretation. In particular,
the traditional practice of using an empirically determined
"cut-off" in the relaxation time distribution becomes
completely invalid unless extensive corrections are made to
correlations obtained at room temperature.

In the context of more advanced models of NMR in
water-saturated rocks, the data is explained only by a
temperature dependence of the intrinsic nuclear magnetic
relaxivity of the rock pore surfaces. The interpretation
methodology recently proposed for dual porosity carbonate
systems of the type known as "peloidal grainstones" or
"peloidal packstones" still delivers an expected length scale
for large, intergranular pores, but fails to deliver a
correct length scale for micropores unless it is extended
using a laboratory determination of relaxivity as a function
of temperature.

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Selecting a laboratory correlation appropriate for the
known geological and mineralogical characteristics of the
sub-surface known a priori from other data, or determined in
situ using other logging tools, it is possible to adapt the
interpretation of the carbonate rock to account for the
temperature dependence. Thus adapted, the methodology
delivers length scales for both the intergranular pores and
the micropores of the dual porosity systems common in
carbonate geology. Although the inferred intergranular pore
length scale should be affected only weakly by the
temperature effect disclosed herein, the micropore length
scale will be affected strongly. Both of these length scales
are important in estimating transport properties such as
electrical conductivity and hydraulic permeability. The
latter is of considerable importance in evaluating subsurface
formations, because it determines how easy it is to produce
the hydrocarbons which may be present. The former is
important, because it affects the interpretation of
associated resistivity logs. The resistivity logs are a
primary source of data for estimating how much hydrocarbons
may be present.

The present invention contemplates two equivalent
methods for obtaining reliable NMR results for bound fluid
and free fluid in carbonate rock formations based upon
adjusting T_2 data with respect to temperature. The invention
also features a more advanced methodology for ascertaining
the rock petrophysical properties, which methodology adapts
another application to include the newly discovered
temperature dependence of relaxivity.

SUMMARY OF THE INVENTION

The aspect of the invention closest to orthodox
practice, features two equivalent methods of achieving
reliable results for bound fluid and free fluid. Orthodox

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practice relies implicitly upon the aforementioned
assumptions of: (2) pore independent; (4) additive
magnetization decays. The invention retains these
assumptions in the first method. The first method allows for
an expected variation of surface relaxivity ρ as found
experimentally in carbonate rocks, within the application of
Eq. 1 of Assumption (3). The methods employ the conventional
T_2 distribution, which is generally regarded as equivalent to
a pore-size distribution, where each pore size "a" (strictly,
volume to surface ratio V/S) is associated with a particular
relaxation time T_2, the proportionality being the surface
relaxivity, as in the equation now found in hundreds of
sources dealing with NMR logging:

$$1/T_2 \; = \; \rho \; S/V \; = \; \rho/a \qquad\qquad (2)$$

Orthodox practice is to determine by laboratory
experiments a so-called "T_2 cut-off" or T_{2c}, which partitions
the distribution into small pores (considered to retain fluid
in flows, hence the term "bound fluid") and larger pores
(which allow fluid to flow, called "free fluid"). This
appears to have a certain validity in experiments conducted
at laboratory or room temperatures.

If, however, ρ must be considered to vary with
temperature, then NMR logging of downhole formations at
temperature Θ results in the first instance in a T_2
distribution appropriate to temperature Θ, which can be
called $g^{(\Theta)}(T_2)$. In the orthodox interpretation paradigm,
each relaxation time T_2 corresponding to a pore size
"a" is given by:

$$a \; = \; \rho(\Theta)\,T_2 \qquad\qquad (3)$$

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But the T_2 cut-off, T_{2c}, is determined at room temperature RT. This corresponds to a critical pore size, a_c:

$$a_c = \rho(RT) T_{2c}. \qquad (4)$$

which determines the partition between bound and free fluid.

To make the traditional interpretation of T_2 distributions, an analyst must now either (i) adjust T_2 distribution $g^{(\Theta)}(T_2)$ to room temperature before applying T_{2c}, or (ii) adjust T_{2c} to borehole temperature Θ before applying the conventional integration to yield bound and free fluid volumes. The procedures are equivalent, but the analysis proceeds by slightly different routes.

In the second, more advanced method of the invention, the so-called "model-based interpretations", which are the subject of the application, Serial No. 08/932,141, filed September 16, 1997 (incorporated herein by reference) are subject to temperature modifications. These "model-based interpretations" relate to the physics of diffusion in typical carbonate pore geometries. This second method avoids, in particular, the aforementioned pore space Assumption (2), viz. that the pores act independently. This is now believed to be incorrect for carbonates. The second method of the invention includes the temperature dependence of the surface relaxivity, a numerical parameter appearing explicitly in the computational models of the prior application.

The first and second methods will be explained in more detail with reference to the subsequent detailed description in the preferred embodiments.

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The temperature at any particular depth in the borehole
can be measured by a thermometer in the NMR tool, or it may
be known from previous temperature measurements in the
borehole or other boreholes in the same field. The
temperature can also be derived from empirical relationships
relating temperature to depth in the oil or gas field in
which the NMR logging is taking place.

It is an object of this invention to provide a new
method of determining the bound fluid and free fluid in
carbonate rocks.

It is another object of the invention to provide an
improved method of using temperature adjusted NMR data to
determine the characteristics of carbonate rocks in model-
based interpretations, which further improves the estimates
of petrophysical parameters by explicit modelling of
diffusion within the pore geometry of the rock.

BRIEF DESCRIPTION OF THE DRAWINGS

A complete understanding of the present invention may be
obtained by reference to the accompanying drawings, when
considered in conjunction with the subsequent detailed
description, in which:

FIGURE 1 illustrates a schematic, in situ, side view of
a typical down hole NMR instrument positioned in a bore hole
for making measurements of the surrounding formations, in
accordance with this invention;

FIGURE 2 shows a flow diagram of the temperature
adjusted NMR logging procedure of this invention;

FIGURE 3 illustrates a flow diagram of an alternate
embodiment of the temperature adjusted NMR logging procedure

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of this invention;

FIGURE 4 shows a graph depicting how the T_2 distribution
is adjusted for temperature utilizing the procedure shown in
FIGURE 2; and

FIGURE 5 illustrates a graph depicting how the T_2
distribution is adjusted for temperature utilizing the
procedure shown in FIGURE 3;

FIGURE 6 depicts a flow diagram of a more advanced
method of NMR logging which illustrates a temperature
modified model of the prior application teachings;

FIGURE 7 shows a graph of example relaxation data which
might be obtained downhole; and

FIGURE 8 illustrates a graph depicting a smoothed curve
of noise-free relaxation data computed by the model-based
inversion procedure expressed in FIGURE 6, and based upon the
actual data shown in FIGURE 7.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Generally speaking, the invention reflects the discovery
that carbonate formations yield unreliable, down hole NMR
results. These results must be corrected for temperature.
The invention features two equivalent methods for obtaining
reliable NMR results for bound fluid and free fluid in
carbonate rock formations based upon adjusting the T_2 data
with respect to temperature.

Now referring to FIGURE 1, a typical NMR tool 13 is
shown. The NMR tool 13 is disposed within a borehole 10,
adjacent formations 11 and 12. The NMR tool 13 is lowered
into the borehole 10 by a wireline 8, which communicates with

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surface instrumentation 7. The face 14 of the tool is
designed to intimately contact the borehole surfaces. A
retractable arm 15 is used for this purpose, and presses the
NMR tool 13 against the wall of the borehole. The tool
comprises a magnetic array 17 and an antenna 18, which are
used to create and measure the oscillating magnetic field
characteristics associated with NMR testing. Certain aspects
of NMR testing also require that the area of investigation be
prepolarized, which is accomplished by component 19. A more
detailed discussion of this tool and others used for bore
hole NMR exploration, can be obtained by reference to United
States Patent No. 5,055,787. The NMR tool illustrated in
FIGURE 1 is excentered in the borehole, and has a sensing pad
that is pushed against the formation, as shown. Other NMR
tools can be centralized in the borehole, such as the tool
described in US Patent No. 4,710,713.

FIGURES 2 and 3 illustrate, by means of respective flow
diagrams 100 and 200, the new temperature adjusted methods of
the invention. The methods utilize the common T_2
distribution, which is generally regarded as equivalent to a
pore-size distribution, in which each pore size "a"
(strictly, volume to surface ratio V/S), is associated with a
particular relaxation time T_2, the proportionality being the
surface relaxivity, as in the equation now found in hundred
of sources dealing with NMR logging:

$$1/T_2 = \rho \, S/V = \rho/a \qquad\qquad (5)$$

Conventional practice is to determine by laboratory
experiments a so-called "T_2 cut-off" or T_{2c}, which partitions
the distribution into small pores, considered to retain fluid
in flows (hence "bound fluid") and larger pores, which allow
fluid to flow (hence "free fluid").

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If, however, ρ is considered to vary with temperature, then NMR logging of down hole formations at temperature Θ results in the first instance in a new T_2 distribution appropriate to temperature Θ, which can be called $g^{(\Theta)}$ (T_2). In the orthodox interpretation paradigm, each relaxation time T_2 corresponding to a pore size "a" is given by:

$$a = \rho(\Theta) T_2 \qquad (6)$$

But the T_2 cut-off, T_{2c}, is determined at room temperature RT. This corresponds to a critical pore size, a_c:

$$a_c = \rho(RT) T_{2c}' \qquad (7)$$

which determines the partition between bound and free fluid.

To make the traditional interpretation of T_2 distributions, the analyst now either (i) adjusts T_2 distribution $g^{(\Theta)}$ (T_2) to room temperature before applying T_{2c}, or (ii) adjusts T_{2c} to borehole temperature Θ before applying the conventional integration to yield bound and free fluid volumes.

To make the traditional interpretation of T_2 distributions, the new method of the invention can either (i) adjust the T_2 distribution $g^{(\Theta)}$ (T_2) to room temperature before applying T_{2c}, or (ii) adjust T_{2c} to borehole temperature Θ before applying the conventional integration to yield bound and free fluid volumes. These equivalent procedures are illustrated in FIGURES 2 and 3, respectively, described in greater detail hereinbelow. The only difference is whether the analyst chooses to present the general display of T_2 data referenced to borehole temperature Θ as shown in FIGURE 3, or

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to room temperature, as illustrated in the method shown in
FIGURE 2.

The method of FIGURE 2 (room temperature referencing) is
consistent with the generic practice of performing
"environmental corrections" to well log data, obtained by an
appropriate tool shown in FIGURE 1. The data is presented in
terms of what would be expected, as if the measurement had
been performed at room temperature, rather than at
temperature Θ.

It is commonly assumed that ρ is uniform throughout the
rock pores. Making this simple assumption, and assuming that
the quantity of fluid in pores of size "a" does not change
with temperature, the pore size can be related to T_2 at the
two temperatures by:

$$a = \rho(RT)T_2(a,RT) = \rho(\Theta)T_2(a,\Theta) \qquad (8)$$

On a logarithmic scale of T_2 (as conventionally used)
this amounts to a shift in the curve for $g^{(\Theta)}$ to obtain $g^{(RT)}$,
by a fixed distance $\log(\rho(\Theta)/\rho(RT))$, where the ratio
$\rho(\Theta)/\rho(RT)$ can be determined in the laboratory. This is the
method shown in FIGURE 2.

FIGURE 4 depicts a graph of free fluid vs. $g(T_2)$. It
can be seen that referencing the data to room temperature
results in shifting the curve leftwardly from $g^{(\Theta)}(T_2)$
to $g^{(RT)}(T_2)$ as a function of temperature correction.

Alternatively, the method of FIGURE 3 can be used to
adjust T_{2c} for temperature, instead, because the critical pore
size a_c dividing free from bound fluid stays the same.
Because of the difference in ρ, consider:

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$$a_c = \rho(RT) T_{2c}(RT) = \rho(\Theta) T_{2c}(\Theta) \qquad (9)$$

or equivalently:

$$T_{2c}(\Theta) = T_{2c}(RT) [\rho(RT)/\rho(\Theta)] \qquad (10)$$

Again, on the conventional log T_2 axis, this amounts to a shift of the position of T_{2c} by an amount of log $(\rho(RT)/\rho(\Theta))$, as shown in FIGURE 5. Note that this is the same distance, but in the opposite sense, to the shift applied to $g^{(\Theta)}$ to obtain $g^{(RT)}$ of FIGURE 4 pursuant to the method of FIGURE 2.

The methods of FIGURES 2 and 3 are mathematically equivalent. However, the method in FIGURE 2 references all of the data to room temperature, which is more consistent with traditional practices of "environmental corrections" in log analysis generally; whereas the method in FIGURE 3 references data to borehole temperature. The method of FIGURE 3 is slightly easier to explain, by reason of the critical pore size a_c, which remains almost unchanged, while its associated relaxation time varies according to any change in relaxivity ρ.

Now referring once again to FIGURE 2, a flow chart 100 of this invention features correcting the data in the borehole for temperature variation of the relaxivity, ρ. The NMR tool 13 (FIGURE 1) is placed in the borehole, step 101. The spin echoes of the NMR relaxation data are measured at temperature Θ, step 102. A T_2 distribution as it relates to temperature Θ is then obtained, step 103. In accordance with the invention, the T_2 distribution must then be temperature corrected with regard to environmental correction, step 104, to obtain the temperature-corrected T_2 distribution, step 105. The results are then displayed and interpreted, step 107. The data is then integrated over the T_2 distribution

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ranges, step 108, delimited by the T_2 cut-off, and the bound
fluid volume and the free fluid index is determined, step
109. The integration step 108 uses the conventional input of
the T_2 cut-off 110 to partition the T_2 distribution. As with
the conventional, prior art method, other well data 111 may
be introduced at point B, along with the measurement of
temperature ⊖, step 112.

Now referring to FIGURE 3, depicting an alternate method
200 of this invention, relaxivity ρ is corrected for
temperature variation in the laboratory (i.e., at room
temperature (RT)). The NMR tool 10 is introduced into the
borehole, step 201. The relaxation data at temperature ⊖ is
measured, step 202. The T_2 distribution is obtained as it
relates to temperature ⊖, with no adjustment for temperature,
step 203. The T_2 cut-off partitioning the T_2 distribution
determined in the laboratory at room temperature RT, step
204, is used in accordance with the invention to carry out
the environmental correction for temperature at the borehole
temperature ⊖, step 205. The new temperature-corrected T_2
cut-off is obtained, step 206. This data is then used to
adjust the T_2 distribution for the integration, step 207,
thus obtaining the bound fluid volume and the free fluid
index, step 208. As with conventional procedures, other well
data 209 can be introduced at point B, while measuring the
temperature ⊖, step 210, which is used to adjust the T_2 cut-
off, steps 205 and 206. The T_2 distribution at temperature ⊖
can be displayed, step 211, for further analysis.

Referring to FIGURE 6, a flow diagram 20 illustrates the
more advanced procedure, used for NMR logging utilizing the
logging tool 13, shown in FIGURE 1. The logging tool 13 is
lowered into the borehole, step 322. NMR relaxation data is
obtained by the tool 13 without adjusting for temperature,
step 324. This data is typically very noisy, as shown in
FIGURE 7. Other well data from the same borehole (block 344)

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can be combined with the temperature data at point B to
obtain accurate data for subsequent method steps (blocks 328,
330 and 332), respectively.

The parameters diffusivity D_0 (block 330), bulk
relaxation T_{2B} (block 332) and relaxivity ρ (block 350) are
determined by laboratory studies, so that they are assumed
known a priori in the flow diagram of Figure 6.

The logging tool 13 measures temperature, block 326, for
inclusion into the temperature dependent physical data of the
interpretation algorithm, steps 328, 330, and 332. The data
includes fluid or mineral material properties, step 328,
diffusivity, step 330, and bulk relaxation time, step 332.
This data is used to construct a model for the NMR response
of a given pore geometry in the rock formation, step 334.

In accordance with the novel aspects of this invention,
surface relaxivity, ρ, which is a property of the mineral
surface, is also used, step 350, to construct the model of
block 334. Until this invention, the relaxivity, ρ, was
never adjusted for temperature shown via line 352.

Trial values for the geometrical parameters of the rock
pores, step 336, are also used to construct the model 334.
Next, simulated relaxation data, step 338, is obtained from
the NMR model 334, and combined at point A with actual
measured NMR relaxation data, step 324. The combined data,
line 340, is used to adjust the geometrical parameters, step
336, to obtain the best fit. At that point, the simulated
relaxation data of step 338 is a "best, least squares fit",
as shown by the smoothed curve in FIGURE 8. Best estimates
of the geometrical parameters are outputed in step 342.
These best estimates are then used to estimate rock
petrophysical characteristics such as permeability, or
electrical resistivity.

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Since other modifications and changes varied to fit particular operating requirements and environments will be apparent to those skilled in the art, the invention is not considered limited to the example chosen for purposes of disclosure, and covers all changes and modifications which do not constitute departures from the true spirit and scope of this invention.

Having thus described the invention, what is desired to be protected by Letters Patent is presented in the subsequently appended claims.

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What is claimed is:

1.   A NMR logging system for obtaining accurate formation
characteristics in a bore hole, comprising:

   a formation probing instrument having means for
measuring NMR relaxation in formations down hole, said
instrument having additional temperature measuring means for
measuring the temperature;

      recording means operatively connected to said formation
probing instrument for recording data of down hole
measurements of relaxation, and temperature; and

      processing means associated with said recording means
for adjusting said relaxation measurements with respect to a
temperature difference between downhole temperature and room
temperature in order to obtain accurate formation
characteristics.

2.   The NMR logging system in accordance with claim 1,
wherein said formation probing instrument comprises a tool
with a sensor pad that is pressed against the formation.

3.   The NMR logging system in accordance with claim 1,
wherein said formation probing instrument comprises an NMR
tool adapted to be centered in the bore hole.

4.   A logging method for obtaining accurate formation
characteristics in a bore hole, comprising the steps of:
      (a) obtaining NMR relaxation data down hole;
      (b) adjusting said obtained NMR relaxation data with
respect to a temperature difference between room temperature
and downhole temperature; and
      (c) utilizing said adjusted NMR relaxation data in
establishing formation characteristics.

5.   The logging method in accordance with claim 3, wherein
said formation comprises carbonate rock.

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6.   A NMR logging system for obtaining accurate formation characteristics in a bore hole, comprising:

a formation probing instrument having means for measuring NMR relaxation in formations down hole, said instrument having additional temperature measuring means for measuring the temperature;

processing means associated with said probing instrument for adjusting said relaxation measurements to downhole temperature; and

recording means operatively connected to said formation probing instrument for recording the adjusted data for providing accurate formation characteristics.

7.   The NMR logging system in accordance with claim 6, wherein said formation probing instrument comprises a tool with a sensor pad that is pressed against the formation.

8.   A logging method for obtaining accurate formation characteristics in a bore hole, comprising the steps of:

(a) obtaining NMR relaxation data down hole;

(b) adjusting said NMR relaxation data for downhole temperature; and

(c) utilizing said NMR relaxation data of step (b) in establishing formation characteristics.

9.   The logging method in accordance with claim 8, wherein said formation comprises carbonate rock.

10. A method for obtaining accurate formation characteristics in a bore hole, comprising the steps of:

a) obtaining NMR relaxation data down hole and obtaining a T_2 distribution $g^{(e)}$ (log T_2) therefrom;

b) environmentally correcting said T_2 distribution data to obtain a T_2 distribution $g^{(RT)}$ (log T_2), that is room temperature referenced;

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c) determining bound fluid volume and free fluid index, dependent upon said relaxation data and said room temperature referenced T_2 distribution; and

d) establishing formation characteristics dependent upon said NMR relaxation data and said temperature referenced T_2 distribution.

11.   The method in accordance with claim 10, the steps further comprising:

e) partitioning said T_2 distribution into bound fluid and free fluid; and

f) integrating said corrected T_2 distribution prior to determining bound fluid volume and free fluid index.

12.   The method in accordance with claim 11, wherein said formation comprises carbonate rock.

13.   A method for obtaining accurate formation characteristics in a bore hole, comprising the steps of:

a) obtaining NMR relaxation data down hole;

b) obtaining a T_2 distribution $g^{(\theta)}$ ($\log T_2$) from said NMR relaxation data;

c) obtaining a T_2 cut-off referenced to borehole temperature;

d) integrating said T_2 distribution over ranges delimited by said temperature referenced T_2 cut-off; and

e) establishing formation characteristics, dependent upon said adjusted NMR relaxation data.

14.   The method in accordance with claim 13, the steps further comprising:

f) determining bound fluid volume and free fluid index, dependent upon said relaxation data and said T_2 distribution.

15.   The method in accordance with claim 13, wherein said formation comprises carbonate rock.

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16. A method for obtaining accurate formation characteristics in a bore hole, comprising the steps of:

    (a) obtaining relaxation data downhole;

    (b) constructing a NMR model for a given pore geometry of a rock formation using geometrical parameters of the rock pores, and, inter alia, temperature dependent surface relaxivity;

    (c) obtaining simulated relaxation data obtained from the NMR model constructed in step (b);

    (d) combining the NMR relaxation data of step (a) with simulated relaxation data of step (c);

    (e) adjusting the geometrical parameters of the rock pores to obtain a best fit; and

    (f) estimating the rock formation characteristics based upon the adjusted geometrical parameters of step (e).

17. The method in accordance with claim 16, wherein the model construction step (b) includes the further step of:

    (g) estimating temperature downhole.

18. The method in accordance with claim 16, wherein the model construction step (b) includes the further step of:

    (g) measuring temperature downhole.

19. The method in accordance with claim 16, wherein the NMR model constructing step (b) includes the further step of:

    (h) using diffusivity D_0 estimated a priori.

20. The method in accordance with claim 16, wherein the NMR model constructing step (b) includes the further step of:

    (h) using bulk relaxation T_{2B} estimated a priori.

21. The method in accordance with claim 16, wherein the NMR model constructing step (b) includes the further step of:

    (h) using surface relaxivity ρ estimated a priori.

20

22. The method in accordance with claim 16, wherein the
model constructing step (b) includes the further steps of:
    (h) deriving downhole temperature;
    (i) estimating diffusivity D_o a priori;
    (j) estimating bulk relaxation T_{2B} a priori; and
    (k) estimating surface relaxivity ρ a priori.

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VOLUME OF
INVESTIGATION

FIG.1

```
         ┌──────────────────┐  ╭─101          ┌──────────────────┐╭─111
         │ NMR LOGGING      │                 │ OTHER WELL DATA  │
         │ TOOL             │                 │ FROM THE SAME    │
         │ IN THE BOREHOLE  │                 │ BOREHOLE         │
         └────────┬─────────┘                 └────────┬─────────┘
                  │            ╲                        │
                  ▼             ╲                       ▼
┌──────────────────────────────┐  ╲              ⬡ AND/
│ NMR RELAXATION DATA          │   ╲            ⬡  OR  ⬡ ──B
│         M_d(t)               │    ╲           ⬡      ⬡
102─│ −A SEQUENCE OF SPIN ECHOES  │    ▼             │
    │ MEASURED AT TEMP. Θ       │                     │
    │ TYPICALLY VERY NOISY      │                     ▼
    └──────────────┬────────────┘        ┌──────────────────────┐
                   │                      │ TEMPERATURE          │
ORTHODOX           ▼                      │       Θ              │
PROCESSING  ┌──────────────────────────┐ └──────────┬───────────┘
INCLUDES NO │ OBTAIN T_2 DISTRIBUTION  │╭─103        ╰─112
TEMPERATURE │ −RELATES TO TEMP. Θ      │
EFFECTS     │    g^(Θ)(log T_2)        │
            └──────────────┬───────────┘                   ╭─100
                           │                          ╭─110
                           ▼
     ┌────────────────────────────────┐      ┌──────────────────────┐
     │ CARRY OUT ENVIRONMENTAL        │      │ THE T_2 CUT−OFF:     │
     │ CORRECTION FOR TEMPERATURE     │◄─────│ PARTITIONS THE       │
104─ │                                │      │ T_2 DISTRIBUTION     │
     │ −ESTIMATES WHAT WOULD HAVE     │      │ INTO BOUND FLUID     │
     │ HAPPENED IF AT ROOM            │      │ AND FREE FLUID:      │
     │ TEMPERATURE (RT)               │      │ DETERMINED BY LAB    │
     └───────────────┬────────────────┘      │ WORK AT RT           │
                     │                        └──────────┬───────────┘
                     ▼
     ┌────────────────────────────────┐
     │ OBTAIN TEMPERATURE             │
105─ │ CORRECTED T_2 DISTRIBUTION     │
     │                                │
     │  g^(RT)(log T_2)               │
     │ −WHAT WE EXPECT TO GET         │
     │ FOR THE SAME ROCK AT           │
     │ ROOM TEMPERATURE               │
     └────┬───────────────────┬───────┘                ORTHODOX
          │                   │                         INPUT
107─      ▼                   ▼
  ╭─────────────────╮  ┌──────────────────────┐
  │ DISPLAY AND     │  │ INTEGRATE OVER RANGES│╭─108
  │ INTERPRET       │  │ OF THE T_2 DISTRIBUTION│
  ╰─────────────────╯  │ DELIMITED BY THE     │
                       │ T_2 CUT−OFF          │
                       └──────────┬───────────┘   ORTHODOX
                                  │                PROCESSING
                                  ▼
                       ┌──────────────────────┐
                       │ BOUND FLUID VOLUME   │╭─109
                       │ AND FREE FLUID INDEX │
                       │ (BFV AND FFI)        │
                       └──────────────────────┘
```

FIG.2

```
┌─────────────────────┐                           ┌─────────────────────┐
│  NMR LOGGING        │──201                      │ OTHER WELL DATA     │──209
│  TOOL               │                           │ FROM THE SAME       │
│  IN THE BOREHOLE    │                           │ BOREHOLE            │
└─────────────────────┘                           └─────────────────────┘
          │                                                  │
          ▼                                                  ▼
┌─────────────────────┐                              ╱─────────╲    B
│ NMR RELAXATION DATA │                             ╱  AND/    ╲──
│      M_d(t)         │                             ╲   OR     ╱── 200
│ -A SEQUENCE OF SPIN │                              ╲─────────╱
│ ECHOES MEASURED     │                                   │      210
│ AT TEMP. Θ          │                                   ▼
│ TYPICALLY VERY NOISY│                           ┌─────────────────────┐
└─────────────────────┘                           │   TEMPERATURE       │
          │                                        │       Θ             │
          ▼                                        └─────────────────────┘
┌─────────────────────┐        204
│ OBTAIN T₂ DISTRIBUTION│                  ORTHODOX INPUT
│ -RELATES TO TEMP. Θ │      ┌─────────────────────────┐
│   g^(Θ)(log T₂)     │      │ THE T₂ CUT-OFF          │
└─────────────────────┘      │ PARTITIONS THE T₂       │
      203                    │ DISTRIBUTION INTO BOUND │
                             │ FLUID AND FREE FLUID:   │
                             │ DETERMINED BY LAB       │
                             │ WORK AT RT (ROOM TEMP.) │
                             └─────────────────────────┘
                                        │
                                        ▼
                             ┌─────────────────────────┐
                             │ CARRY OUT ENVIRONMENTAL │
                             │ CORRECTION FOR TEMPERATURE│
                             │                         │
                             │ -ESTIMATES WHAT WOULD HAVE│
                      205    │ HAPPENED IF AT BOREHOLE │
                             │ TEMPERATURE Θ           │
                             └─────────────────────────┘
                                        │
┌─────────────────────┐                 ▼
│DISPLAY AND INTERPRET│       ┌─────────────────────────┐
└─────────────────────┘       │ OBTAIN TEMPERATURE-     │
  211                         │ CORRECTED T₂ CUT-OFF    │
                             │ -WHAT WE EXPECT TO GET FOR│
┌─────────────────────┐      │ THE SAME TYPES OF ROCK AS│
│ INTEGRATE OVER RANGES│     │ USED IN LAB TESTS,      │
│ OF THE T₂ DISTRIBUTION│    │ IF THEY HAD BEEN DONE AT│
│ DELIMITED BY THE    │      │ BOREHOLE TEMPERATURE Θ  │
│ T₂ CUT-OFF          │      └─────────────────────────┘
└─────────────────────┘                    206
  207
                                  ORTHODOX
┌─────────────────────┐           PROCESSING
│ BOUND FLUID VOLUME  │
│ AND FREE FLUID INDEX│──208
│ (BFV AND FFI)       │
└─────────────────────┘
```

ORTHODOX
PROCESSING
INCLUDES NO
TEMPERATURE
EFFECTS

200

FIG.3

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REFERENCES DISTRIBUTION
AND CUT-OFF TO ROOM
TEMPERATURE.
(Re: FIG.3)

$g^{(RT)}(T_2)$

$g^{(\theta)}(T_2)$

TEMPERATURE CORRECTION
OF T_2 DISTRIBUTION

log T_2

BOUND FLUID

FREE FLUID
(SHADED VOLUME)

T_{2C} —THE T_2 CUT-OFF

(FOUND AT ROOM TEMPERATURE)

FIG.4

REFERENCES DISTRIBUTION
AND CUT-OFF TO BOREHOLE
TEMPERATURE.
(Re: FIG.4)

TEMPERATURE CORRECTION
OF T_2 CUT-OFF

$g^{(\theta)}(T_2)$

log T_2

BOUND FLUID

FREE FLUID
(SHADED VOLUME)

$T_{2C}^{(\theta)}$ —THE "CORRECTED" T_2 CUT-OFF
(EXPECTED FOR TEMP. θ)

$T_{2C}^{(RT)}$ —THE T_2 CUT-OFF
(FOUND AT ROOM TEMPERATURE)

FIG.5

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```
┌─────────────────┐                    ┌─────────────────────┐
│ NMR LOGGING     │ ⌐322               │ OTHER WELL DATA     │⌐344
│ TOOL            │                    │ FROM THE SAME       │
│ IN THE BOREHOLE │                    │ BOREHOLE            │
└─────────────────┘                    └─────────────────────┘
```

```
                    ┌──────────────────────┐
ORTHODOX            │ NMR RELAXATION DATA   │                        ⟋B
PROCESSING         │      M_d(t)           │⌐324          ⬡ AND/
INCLUDES NO    ◄───│ -A SEQUENCE OF SPIN   │               OR
TEMPERATURE        │ ECHOES MEASURED       │                      ⌐320
EFFECTS            │ AT TEMP. ϴ            │
                   │ TYPICALLY VERY NOISY  │              ┌─────────────────┐ ⌐326
A ╲               └──────────────────────┘               │  TEMPERATURE    │
 ⊗                                                        │      ϴ          │
                                                          └─────────────────┘
```

$M_d(t)$

$M(t)$

SIMULATED RELAXATION
DATA M(t)
-A SMOOTH DECAY CURVE
CALCULATED FOR BOREHOLE
TEMP. ϴ
338

LOOP TO
FIND BEST
FIT

MODEL: FOR NMR
RESPONSE OF GIVEN PORE
GEOMETRY IN ROCK
334

340

336

GEOMETRICAL PARAMETERS
OF ROCK PORES:
POROSITIES AND SIZES

ADJUST
TRIAL VALUES

342

BEST ESTIMATES OF THE
GEOMETRICAL PARAMETERS
OF ROCK PORES

TEMPERATURE
VARIATION OF FLUID
OR MINERAL
MATERIAL PROPERTIES   ⌐328

DIFFUSIVITY D_0 ⌐330

BULK RELAXATION
TIME OF FLUID T_{2B} ⌐332

SURFACE RELAXIVITY ρ ⌐350
(PROPERTY OF MINERAL
SURFACE)

352

ROCK FORMATION CHARACTERISTICS
DETERMINED FROM THESE
PARAMETERS

FIG.6

MAGNETIZATION DECAY IN CORE SAMPLE 9145V

FIG.7

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FIG.8