(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
18 December 2008 (18.12.2008)

PCT

(10) International Publication Number
WO 2008/154635 A1

(51) International Patent Classification:
G01V 5/10 (2006.01)

(21) International Application Number:
PCT/US2008/066726

(22) International Filing Date: 12 June 2008 (12.06.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/943,451 12 June 2007 (12.06.2007) US
61/037,513 18 March 2008 (18.03.2008) US

(71) Applicant *(for all designated States except US)*: **BAKER HUGHES INCORPORATED** [US/US]; 2929 Allen Parkway, Suite 2100, Houston, TX 77019-2118 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **FERGUSON, Grant, V.** [US/CA]; 279 Hamptons Terrace Nw, Calgary, Alberta, T3A 5R4 (CA).

(74) Agents: **RIDDLE, J., Albert** et al.; Baker Hughes Incorporated, P.O. Box 4740, Houston, TX 77027-4740 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(54) **Title:** USE OF ELEMENTAL PULSE NEUTRON SPECTROSCOPY MEASUREMENTS FOR INDEXING BITUMEN VISCOSITY IN THE WELL

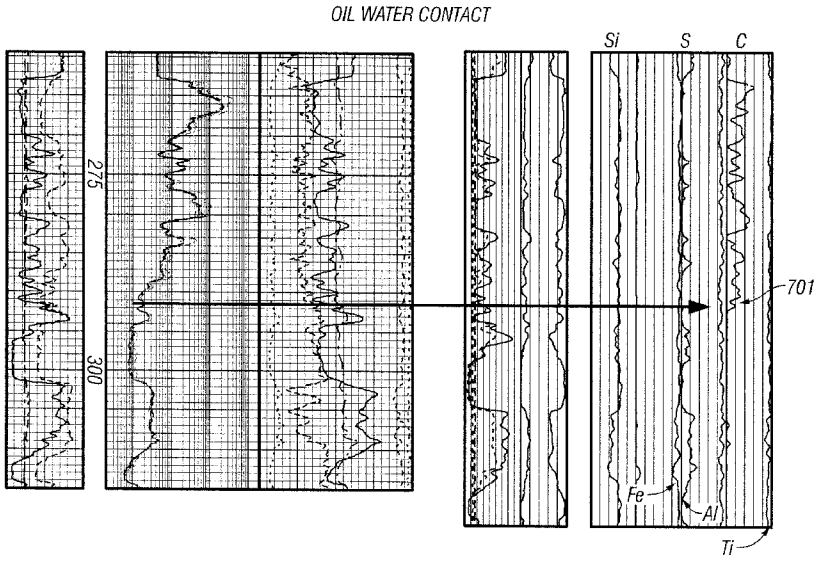

FIG. 7

(57) **Abstract:** Elemental analysis of an earth formation is obtained using measurements from a gamma ray logging tool. From the elemental analysis, an estimate of the carbon content and the sulfur, vanadium, nickel, titanium and/or molybdenum content of the formation is determined. A table look-up is used to estimate the viscosity from the elemental composition.

WO 2008/154635 A1

USE OF ELEMENTAL PULSE NEUTRON SPECTROSCOPY MEASUREMENTS FOR INDEXING BITUMEN VISCOSITY IN THE WELL

Inventor: Grant V. Ferguson

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

[0001] The present disclosure is in the field of pulsed neutron gamma ray excitation testing of geological formations. In particular, the disclosure determines the viscosity of a formation fluid from recorded spectra.

2. Description of the Related Art

[0002] Enormous amounts of hydrocarbon reserves occur in the form of heavy oil and tar sand bitumens produced by a process of biodegradation. In such deposits, significant vertical and lateral gradients in the oil composition and oil viscosity can result. In deposits of such sands, recovery of hydrocarbons may be done by steam injection in situ or by strip mining the deposits and processing the recovered material. An important aspect of the recovery operation is the amount of heat or steam needed, and the subsequent processing that is necessary. This, in turn, is directly correlated with the viscosity of the sands. In situ measurements of viscosity measurements are thus of great value in evaluating prospective deposits of oil sands and in the recovery of hydrocarbons from them. *Gabitto and Barrufet* have done an extensive study of the viscosity of heavy oils and developed a correlation model relating the viscosity to boiling point, API gravity and molecular weight. All of these determinations require recovery of an actual sample of the oil (a laborious procedure in itself) and further laboratory measurements.

[0003] NMR techniques have also been used for distinguishing between heavy oil and water. See, for example US Patent No. 6,755,246 to *Chen* et al., having the same assignee as the present disclosure. As noted therein, elevated temperatures are necessary to accomplish this. NMR methods are complicated, and the elevated temperatures necessary for the method of *Chen* adds further complication. The present disclosure addresses this problem using the novel approach of elemental analysis of gamma ray spectra made with a logging tool.

[0004] Well logging systems have been utilized in hydrocarbon exploration for many years. Such systems provide data for use by geologists and petroleum engineers in making many determinations pertinent to hydrocarbon exploration and production. In particular, these systems provide data for subsurface structural mapping, defining the lithology of subsurface formations, identifying hydrocarbon-productive zones, and interpreting reservoir characteristics and contents. Many types of well logging systems exist which measure different formation parameters such as conductivity, travel time of acoustic waves within the formation and the like.

[0005] One class of systems seeks to measure incidence of nuclear particles on the well logging tool from the formation for purposes well known in the art. These systems take various forms, including those measuring natural gamma rays from the formation. Still other systems measure gamma rays in the formation caused by bursts of neutrons into the formation by a neutron source carried by the tool and pulsed at a preselected interval.

[0006] In these nuclear well logging systems, reliance is made upon the physical phenomenon that the energies of gamma rays given off by nuclei resulting from natural radioactive decay or induced nuclear radiation are indicative of the presence of certain elements within the formation. In other words, formation elements will react in predictable ways, for example, when high-energy neutrons on the order of 14.2 MeV collide with the nuclei of the formation elements. Different elements in the formation may thus be identified from characteristic gamma ray energy levels released as a result of this neutron bombardment. Thus, the number of gamma rays at each energy level will be functionally related to the quantity of each element present in the formation, such as the element carbon, which is present in hydrocarbons. The presence of gamma rays at a 2.2 MeV energy level may for example, indicate the presence of hydrogen, whereas predominance of gamma rays having energy levels of 4.43 and 6.13 MeV, for example, may indicate the presence of carbon and oxygen respectively.

[0007] In these nuclear well logging systems, it is frequently useful to obtain data regarding the time spectral distributions of the occurrence of the gamma rays. Such data can yield extremely valuable information about the formation, such as

identification of lithologies that are potentially-hydrocarbon producing. Moreover, these desired spectral data may not only be limited to that of natural gamma rays, for example, but also may be desired for the gamma ray spectra caused by bombardment of the formation with the aforementioned pulsed neutron sources.

[0008] Well logging systems for measuring neutron absorption in a formation use a pulsed neutron source providing bursts of very fast, high-energy neutrons. Pulsing the neutron source permits the measurement of the macroscopic thermal neutron absorption capture cross-section Σ of a formation. The capture cross-section of a reservoir rock is indicative of the porosity, formation water salinity, and the quantity and type of hydrocarbons contained in the pore spaces.

[0009] The measurement of neutron population decay rate is made cyclically. The neutron source is pulsed for 20-40 microseconds to create a neutron population. Neutrons leaving the pulsed source interact with the surrounding environment and are slowed down. In a well logging environment, collisions between the neutrons and the surrounding fluid and formation atoms act to slow these neutrons. Such collisions may impart sufficient energy to these atoms to leave them in an excited state, from which after a short time gamma rays are emitted as the atom returns to a stable state. Such emitted gamma rays are labeled inelastic gamma rays. As the neutrons are slowed to the thermal state, they may be captured by atoms in the surrounding matter. Atoms capturing such neutrons are also caused to be in an excited state, and after a short time gamma rays are emitted as the atom returns to a stable state. Gamma rays emitted due to this neutron capture reaction are labeled capture gamma rays. In wireline well logging operations, as the neutron source is pulsed and the measurements made, the subsurface well logging instrument is continuously pulled up through the borehole. This makes it possible to evaluate formation characteristics over a range of depths.

[0010] Depending on the material composition of the earth formations proximal to the instrument, the thermal neutrons can be absorbed, or "captured", at various rates by certain types of atomic nuclei in the earth formations. When one of these atomic nuclei captures a thermal neutron, it emits a gamma ray, which is referred to as a "capture gamma ray".

[0011] Prior art methods exist for determining attributes of a formation from logging results. See, for example, U.S. Patent No. 4,712,424, to *Herron*, U.S. Patent No. 4,394,574, to *Grau* et al., U.S. Patent No. 4,390,783, to *Grau*, SPE 7430, SPE9461, and U.S. Patent No. 5,471,057, to *Herron*.

SUMMARY OF THE DISCLOSURE

[0012] One embodiment of the disclosure is a method of estimating a viscosity of a fluid in an earth formation. The method includes conveying a tool into a borehole in the earth formation and pulsing the formation with radiation from the tool. Gamma rays resulting from interaction of the pulsed radiation with nuclei in the formation are detected. From a determined spectrum of the gamma rays, an elemental concentration of elements in the formation that are correlated with fluid viscosity is determined. The radiation may include neutrons. The detected gamma rays may include inelastic gamma rays and/or capture gamma rays. The determined spectrum may include an inelastic spectrum. The estimated elements may include sulfur, nickel, titanium, vanadium and/or molybdenum. From the estimated concentration of elements, a table lookup may be performed to determine the formation hydrocarbon fluid viscosity.

[0013] Another embodiment of the disclosure is an apparatus for estimating a viscosity of a fluid in an earth formation. The apparatus includes a tool configured to be conveyed in a borehole in the earth formation. The tool includes a radiation source configured to pulse the earth formation with radiation and at least one detector configured to detect gamma rays resulting from interaction of the radiation with the formation. A processor is configured to determine a spectrum of the detected gamma rays and estimate from the determined spectrum an elemental concentration of elements that are correlated with formation viscosity. The radiation source may be a neutron source. The detected gamma rays may include inelastic gamma rays and/or capture gamma rays. The determined spectrum may include an inelastic spectrum. The processor may be configured to estimate the elemental concentration by using an inelastic spectrum. The processor may be configured to estimate the elemental concentration of sulfur, nickel, titanium, vanadium and/or molybdenum. From the estimated concentration of elements, processor may be configured to perform a table lookup to determine the formation hydrocarbon fluid viscosity.

[0014] Another embodiment of the disclosure is a computer-readable medium for use with an apparatus for evaluating an earth formation. The apparatus includes a tool configured to be conveyed in a borehole in the earth formation. The tool includes a radiation source configured to pulse the earth formation with radiation and at least one detector configured to detect gamma rays resulting from interaction of the radiation with nuclei in the earth formation. The medium includes instructions which enable a processor to determine a spectrum of the detected gamma rays and to estimate from the determined spectrum an elemental concentration of elements in the formation that are correlated with formation viscosity. The machine readable medium may be a ROM, an EPROM, an EEPROM, a Flash Memory, and/or an Optical disk.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The present disclosure is best understood with reference to the accompanying figures in which like numerals refer to like elements and in which:

FIG. 1 (Prior Art) illustrates a nuclear well logging configuration in accordance with the present disclosure;

FIG. 2 shows an instrument suitable for use with the present disclosure;

FIG. 3 shows the basic timing of the pulsed neutron source and the produced gamma rays;

FIG. 4 shows capture and inelastic spectra from limestone formation with an oil-filled borehole;

FIG. 5 shows the scales used for display of different elements in **FIGS. 6-7**;

FIG. 6 shows the elemental composition display in a shaly interval; and

FIG. 7 shows elemental composition near the oil-water contact.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0016] Referring now to the drawings in more detail, and particularly to **FIG. 1**, there is illustrated a nuclear well logging configuration in accordance with the present disclosure. Well **10** penetrates the earth's surface and may or may not be cased depending upon the particular well being investigated. Disposed within well **10** is subsurface well logging instrument **12**. The system diagramed in **FIG. 1** is a microprocessor-based nuclear well logging system using multi-channel scale analysis for determining the timing distributions of the detected gamma rays. Well logging

instrument **12** includes long-spaced (LS) detector **14**, short-spaced (SS) detector **16** and pulsed neutron source **18**. In an exemplary embodiment, LS and SS detectors **14** and **16** are comprised of bismuth-germanate (BGO) crystals coupled to photomultiplier tubes. To protect the detector systems from the high temperatures encountered in boreholes, the detector system may be mounted in a Dewar-type flask. Also, in an exemplary embodiment, source **18** comprises a pulsed neutron source using a D-T reaction wherein deuterium ions are accelerated into a tritium target, thereby generating neutrons having an energy of approximately 14 MeV. The filament current and accelerator voltage are supplied to source **18** through power supply **15**. Cable **20** suspends instrument **12** in well **10** and contains the required conductors for electrically connecting instrument **12** with the surface apparatus.

[0017] The outputs from LS and SS detectors **14** and **16** are coupled to detector board **22**, which amplifies these outputs and compares them to an adjustable discriminator level for passage to channel generator **26**. Channel generator **26** converts the output pulse heights to digital values, which are accumulated into pulse height spectra, in which the pulses are sorted according to their amplitudes into a discrete array of bins. The bins uniformly divide the entire amplitude range. These pulse height spectra are accumulated in registers in the spectrum accumulator **28**, the spectra being sorted according to their type: inelastic, capture, or background. After a pulse height spectrum has been accumulated, CPU **30** controls the transfer of the accumulated data to the modem **32**, which is coupled to cable **20** for transmission of the data over a communication link to the surface apparatus. To be explained later are further functions of CPU **30** in communicating control commands which define certain operational parameters of instrument **12** including the discriminator levels of detector board **22**, and the filament current and accelerator voltage supplied to source **18** by power supply **15**.

[0018] The surface apparatus includes master controller **34** coupled to cable **20** for recovery of data from instrument **12** and for transmitting command signals to instrument **12**. There is also associated with the surface apparatus depth controller **36** which provides signals to master controller **34** indicating the movement of instrument **12** within well **10**. An input terminal may be coupled to master controller or processor **34** to allow the system operator to provide selected input into master

controller **34** for the logging operation to be performed by the system. Display unit **40**, and storage unit **44** coupled to the master controller **34** may be provided. The data may also be sent by a link to a remote location. Processing may be done either by the surface processor, at the remote site, or by a downhole processor.

[0019] In a well logging operation such as is illustrated by **FIG. 1**, master controller **34** initially transmits system operation programs and command signals to be implemented by CPU **30**, such programs and signals being related to the particular well logging operation. Instrument **12** is then caused to traverse well **10** in a conventional manner, with source **18** being pulsed in response to synchronization signals from channel generator **26**. Typically, source **18** is pulsed at a rate of 10,000 bursts/second (10 kHz). This, in turn, causes a burst of high-energy neutrons on the order of 14 MeV to be introduced into the surrounding formation to be investigated. In a manner previously described, this population of high energy neutrons introduced into the formation will cause the generation of gamma rays within the formation which at various times will impinge on LS and SS detectors **14** and **16**. As each gamma ray thus impinges upon the crystal-photomultiplier tube arrangement of the detectors, a voltage pulse having an amplitude functionally related to the energy of the particular gamma ray is delivered to detector board **22**. It will be recalled that detector board **22** amplifies each pulse and compares them to an adjustable discriminator level, typically set at a value corresponding to approximately 100 keV. If such pulse has an amplitude corresponding to an energy of at least approximately 100 keV, the voltage pulse is transformed into a digital signal and passed to channel generator **26** of MCS section **24**.

[0020] **FIG. 2** illustrates a schematic diagram of an instrument suitable for use with the present disclosure. The Formation Lithology Explore (FLEX^{TM}) is a wireline instrument designed to provide formation mineralogical information, shale identification, and clay typing. The enhanced mineralogical data obtained from the FLEX^{TM} also enables enhanced porosity measurements. The present disclosure is usable in open-hole wireline logging systems. In a typical embodiment, the present disclosure uses the ECLIPS^{TM} acquisition system of Baker Hughes Incorporated. Alternatively, the present disclosure can be used, for example, with the FOCUS system of Baker Hughes, Incorporated. Also, under most conditions, the FLEX^{TM} is

run in combination with Gamma Ray/Spectralog, Neutron, and Density nuclear tools in addition to tools such as resistivity, acoustics, NMR and others. The FLEX™ utilizes an axial pulsed neutron generator of the same type as that used in the reservoir performance monitor instruments. Thus, there are no special storage or transportation requirements except those of a regulatory nature associated with pulsed neutron generators. The logging speed is dependent upon the environment. A typical logging speed is in the range of 15-30 ft/min.

[0021] The FLEX™ measurement device of **FIG. 2** employs the principle of neutron-induced gamma ray spectroscopy. FLEX™ component parts are encapsulated within wireline device casing **200**. The neutron source of the present disclosure is typically a pulsed neutron source. The use of a pulsed neutron source is advantageous over the use of a chemical neutron source due to its ability to generate inelastic gamma rays over a wider range of energies. It also allows a spectrum of capture gamma rays to be generated which is free from inelastic gamma ray contamination, which can also be corrected for background activation gamma rays. Neutron source **209** discharges high-energy bursts of neutrons into the surrounding formation. The electronic pulsed neutron generator is typically operated at a rate of approximately 10,000 Hz, so that each burst takes place within a 100 microsecond window. Gamma rays produced via interaction of the discharged neutrons and the formation are detected at the scintillation detector **212** attached to acquisition and telemetry electronics **215**. Power supply **201** enables the FLEX device. Electronics **203** enables the neutron source. A shield **220** attenuates the neutron flux propagating directly from the source to the detector as well as attenuating gamma rays generated within the shield.

[0022] **FIG. 3** illustrates the basic timing of the pulsed neutron source and the produced gamma rays. Time is displayed along the x-axis in microseconds. The gamma ray counts per second (cps) is displayed along the y-axis. The neutron burst is over a time interval **221** and defines a first-detector-gate interval, referred to as the "burst gate" or inelastic gate. A total spectrum **225** of gamma rays resulting from both inelastic neutron scattering and capture gamma ray scattering is produced during the active duration of the neutron source, and the timing of the inelastic gate enables obtaining the total spectrum. In the example of **FIG. 3**, the number of counts rises significantly (typically to 10^5) during the inelastic gate, which extends approximately

from 10 μsec to 40 μsec. The deactivation of the neutron source causes the inelastic gamma rays to disappear from the count almost immediately. A "dead-zone" is shown at a point substantially coincident with deactivation of the neutron source. This dead-zone extends approximately from 40 μsec to 50 μsec. The counts obtained during this interval are not recorded. The dead-zone is followed by a "capture gate" **223**. The capture gate contains gamma rays substantially due to captured neutrons from the surrounding formation.

[0023] In an exemplary embodiment of the present disclosure, energized neutrons are injected from a pulsed neutron source **209** into a surrounding formation. The scintillation detector records the spectrum over a predetermined time interval. During the inelastic gate, a total spectrum **225** of gamma rays is obtained from the formation layer. A portion of the total spectrum **227** is attributable to capture gamma rays. During a capture gate, a capture spectrum of gamma rays is obtained from the formation layer. A determinable factor of the capture spectrum is subtracted from the obtained total spectrum to derive a spectrum substantially representative of an inelastic spectrum only. The elemental contribution to the inelastic spectrum and the capture spectrum can then be obtained by determining a set of constituent spectra from the inelastic spectrum and a set of constituent spectra from the capture spectrum. These constituent spectra are characteristic of individual elements and are referred to as "elemental standards." An operator versed in the arts can then use the determined elemental contributions to determine a parameter of the surrounding formation.

[0024] The derived gamma ray energy spectra for data analysis comprise both the capture spectrum and the inelastic spectrum. An inelastic gamma ray is generated from the nucleus of the atom from which there is a scattering of initial highly energetic neutrons. A capture gamma ray is emitted by the nucleus of an atom through absorption of a neutron after its energy has diminished. **FIG. 4** shows capture and inelastic spectra from limestone formation with oil-filled borehole. The three spectra are the inelastic spectrum **401**, the capture spectra **402**, and the background spectrum **403**.

[0025] A feature of the present disclosure is the analysis of separate inelastic and capture spectra in terms of their constituent spectra. Prior art discusses methods for

removing the effects of a capture spectrum from a total spectrum obtained during a burst gate, consequently obtaining an improved inelastic spectrum. A corrected fraction of the capture spectrum is subtracted from the total spectrum in order to generate a representative inelastic spectrum. The corrected fraction is referred to as the capture subtraction factor. The method for calculating this value comprises using a capture gamma ray response function to estimate the capture and inelastic components within a recorded time spectrum. Analysis of the spectra can be performed uphole or downhole using a processor or expert system.

[0026] A library of elemental basis functions can be used to enable a decomposition of at least one of capture and inelastic spectra into their respective constituent spectra. As described in US Patent Application Ser. No. 11/ 223,352 of *Pemper* et al., having the same assignee as the present application and the contents of which are incorporated herein by reference, a partial list of elements includes H, C, O, S, Al, Ca, Cl, Fe, Mg, Si. Currently, constituent spectra representing up to 20 elements are usable in the disclosure of *Pemper*. When the fraction of a particular element obtained from both the capture and inelastic spectrum are reasonably close, then their average value may be used for the elemental analysis. Large differences between estimates for a particular element obtained by capture and inelastic spectral decomposition should serve as a cautionary flag. As part of the spectral decomposition using basis functions, it is standard practice to also estimate uncertainties along with the regression coefficients. These uncertainties can be used to provide an estimate of the amount of an element from the individual estimates obtained from inelastic and capture spectra. The number of elements can be increased and is not meant as a limitation of the present disclosure. Elemental basis functions could further be produced using various methods. For example, use of a computer can enable generation of an elemental basis function of a previously unlisted element.

[0027] The present disclosure is based on the recognition of the fact that the elemental composition of biodegraded oil changes with the amount of degradation, and that this is strongly correlated with changes in viscosity of the oil. Hence measurements of the elemental composition can be correlated with viscosity. For example, in a set of genetically related oils from Oklahoma, *Miller* et al. (1987) found the following changes in oil properties with increasing levels of biodegradation:

Table 1 (Prior art)

	API Gravity	Sulfur (wt%)	Vanadium (ppm)	Nickel (ppm)
Non-degraded Oil	**32**	**0.6**	**30.6**	**16.4**
Moderately Biodegraded Oil	**12**	**1.6**	**224**	**75.1**
Heavy Biodegradation (Tar Sand)	**4**	**1.5**	**137.5**	**68.5**

As can be seen, the low gravity (high viscosity) oils have the highest content of sulfur, vanadium and nickel. High values of sulfur, nitrogen, nickel and vanadium have also been noted by *Gray* (1994) in Canadian tar sands and are summarized in Table 2:

Table 2 (prior art)

	Sulfur wt %	Nitrogen wt %	Nickel ppm	Vanadium ppm
Athabasca	5.14	0.56	150	290
Cold Lake	5.10	0.45	200	490
Lloydminster	4.69	0.53	140	190
Peace River	7.02	0.63	130	410

[0028] We next note the following table of thermal capture neutron cross-sections (from the Environmental Chemist):

Table 3

Element	Cross section (barns)
Hydrogen	.3326
Carbon	.0035
Oxygen	.00019
Silicon	.171
Aluminum	.232
Calcium	.43
Chlorine	35.5
Iron	2.56
Magnesium	.063
Silicon	.171
Sulfur	.53
Vanadium	5.08
Titanium	6.09
Molybdenum	2.66

The overall capture cross section of the metals vanadium, titanium and molybdenum and of sulfur is quite large. However, from the standpoint of elemental spectral analysis, sharp peaks in the spectra are more important for resolvability than the total cross section.

[0029] As noted in Bartholomew and Kinsey (1953) Physical Review, vol. 89, Issue 2, pp. 386-395: "Vanadium produces several strong γ-rays with intensities of about 10 photons per 100 captures. Of these, the γ-ray with the highest energy, 7.305±0.007 Mev, can be identified with the transition to the ground state of V^{52}. A group of partially resolved γ-rays with energies between 7.6 and 8.0 Mev are tentatively ascribed to capture in the rare isotope V^{50}. If this interpretation is correct, the isotopic capture cross section of V^{50} probably lies between 40 and 400 barns."

[0030] As noted further in Bartholomew and Kinsey, Physical Review, vol. 89, Issue 2, pp. 375-385: "Titanium emits a very simple spectrum. Two strong γ-rays, 6.756±0.006 and 6.412±0.006 Mev, are produced by capture in Ti^{48}. Neither the direct transition to the ground state of Ti^{49}, nor the transitions to the ground states of Ti^{48} and Ti^{50} were detected. .... nickel spectrum contains an intense γ-ray with an energy

of 8.997±0.005 Mev, which is produced in 50 percent of the captures in Ni^{58}. Another prominent γ-ray at 8.532±0.008 Mev may represent the transition to the ground state in Ni^{61}; if so, it accounts for some 80 percent of captures in Ni^{60}."

[0031] Based on the above, and the fact that sulfur is known to be detectable, we conclude that the elements most characteristic of biodegradation can be detected using gamma ray spectroscopy. As noted in Table 1, there is a strong correlation between viscosity and the elements sulfur, nickel and vanadium. In addition, there are processes aimed are recovering titanium from the tar sand deposits. See US Pat. Pub. 2004/0035755 of *Reeves* and US Patent No. 3,990,885 to *Baillie* et al. The present disclosure envisages using lookup tables to relate the fraction of the different elements discussed above to the viscosity. The disclosure also envisages using the ratio of the elements sulfur, vanadium, nickel, titanium and/or molybdenum to the fraction of a common element such as carbon (representing the bulk of the hydrocarbons) for estimation of viscosity.

[0032] We next show examples of field logs illustrating the principle of the method. **FIG. 5** shows the eight elements that are displayed in the plots of **FIGS. 6-7** and the scales of the display. Note that the elements in the upper row have scales running in the opposite direction to the elements in the lower row. This makes the displays easier.

[0033] **FIG. 6** shows the elemental display in a shaly sand interval. As expected, the Si content is high. There is very little Ti. **FIG. 7** shows a lower section of the well including the oil-water (actually, bitumen-water) contact **701**. There is an increasing amount of Fe, S, Al and Ti compared to the section in **FIG. 6**, indicating increasing biodegradation. At the oil-water contact, the C content drops abruptly. Thus, the ratio of the elemental concentration of Iron, Sulfur, Aluminum and/or Titanium to the total bitumen content (indicated by the Carbon measurement) may be used as an indication of biodegradation.

[0034] The disclosure has been described in terms of measurements made using logging tools conveyed on a wireline device in a borehole. The method can also be used using data obtained by sensors conveyed on a slickline. The method can also be

used on data obtained using measurement-while-drilling sensors conveyed on a drilling tubular. The processing of the data may be done downhole using a downhole processor or at the surface with a surface processor. It is also possible to store at least a part of the data downhole in a suitable memory device, in a compressed form if necessary. Upon subsequent retrieval of the memory device during tripping of the drillstring, the data may then be retrieved from the memory device and processed uphole.

[0035] Implicit in the processing of the data is the use of a computer program on a suitable machine-readable medium that enables the processor to perform the control and processing. The machine-readable medium may include ROMs, EPROMs, EEPROMs, Flash Memories and Optical disks

[0036] While the foregoing disclosure is directed to the specific embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all such variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

CLAIMS

What is claimed is:

1. A method of estimating a viscosity of a fluid in an earth formation, the method comprising:
   (a) conveying a tool into a borehole and pulsing the formation with radiation from the tool;
   (b) detecting gamma rays resulting from interaction of the pulsed radiation with the nuclei in the formation,
   (c) estimating a spectrum of the detected gamma rays; and
   (d) using the estimated spectrum to estimate an elemental concentration of elements that are correlated with a viscosity of the fluid in the earth formation.

2. The method of claim 1 wherein pulsing the formation further comprises using pulsed neutrons.

3. The method of claim 1 wherein detecting the gamma rays further comprises detecting at least one of: (i) inelastic gamma rays, and (ii) capture gamma rays.

4. The method of claim 1 wherein estimating the spectrum further comprises estimating an inelastic spectrum.

5. The method of claim 1 wherein estimating the elemental concentration further comprises estimating a concentration of at least one of: (i) sulfur, (ii) nickel, (iii) titanium, (iv) vanadium, and (v) molybdenum.

6. The method of claim 1 further comprising using the estimated elemental composition to provide an estimate of the viscosity of the fluid.

7. The method of claim 1 further comprising using the estimated elemental composition and an estimate of elemental carbon in the earth formation to estimate the viscosity of the fluid.

8. An apparatus for estimating a viscosity of a fluid in an earth formation, the apparatus comprising:
   (a) a tool configured to be conveyed into a borehole and pulse the formation with radiation;
   (b) a detector configured to detect gamma rays resulting from interaction of the pulsed radiation with the nuclei in the formation, and
   (c) at least one processor configured to:
      (I) estimate a spectrum of the detected gamma rays; and
      (II) use the estimated spectrum to estimate an elemental concentration of elements that are correlated with a viscosity of a hydrocarbon in the earth formation.

9. The apparatus of claim 8 wherein the pulsed radiation comprises neutrons.

10. The apparatus of claim 8 wherein the detector is configured to detect at least one of: (i) inelastic gamma rays, and (ii) capture gamma rays.

11. The apparatus of claim 8 wherein processor is further configured to estimate an inelastic spectrum.

12. The apparatus of claim 8 wherein the processor is further configured to estimate a concentration of at least one of: (i) sulfur, (ii) nickel, (iii) titanium, (iv) vanadium, and (v) molybdenum.

13. The apparatus of claim 8 wherein the at least one processor is further configured to use the estimated elemental composition to provide an estimate of the viscosity of the fluid.

14. The apparatus wherein the tool is configured to be conveyed into the borehole on a conveyance device selected from: (i) a wireline, and (ii) a drilling tubular.

15. A computer-readable medium for use with an apparatus for analyzing an earth formation, the apparatus comprising:

(a) a tool configured to be conveyed into a borehole and pulse the formation with radiation; and

(b) a detector configured to detect gamma rays resulting from interaction of the pulsed radiation with the nuclei in the formation,

the medium comprising instructions that enable at least one processor to: and

(c) estimate a spectrum of the detected gamma rays; and

(d) use the estimated spectrum to estimate an elemental concentration of elements that are correlated with a viscosity of a hydrocarbon in the earth formation.

16. The medium of claim 15 further comprising at least one of: (i) a ROM, (ii) an EPROM, (iii) an EEPROM, (iv) a flash memory, and (v) an optical disk.

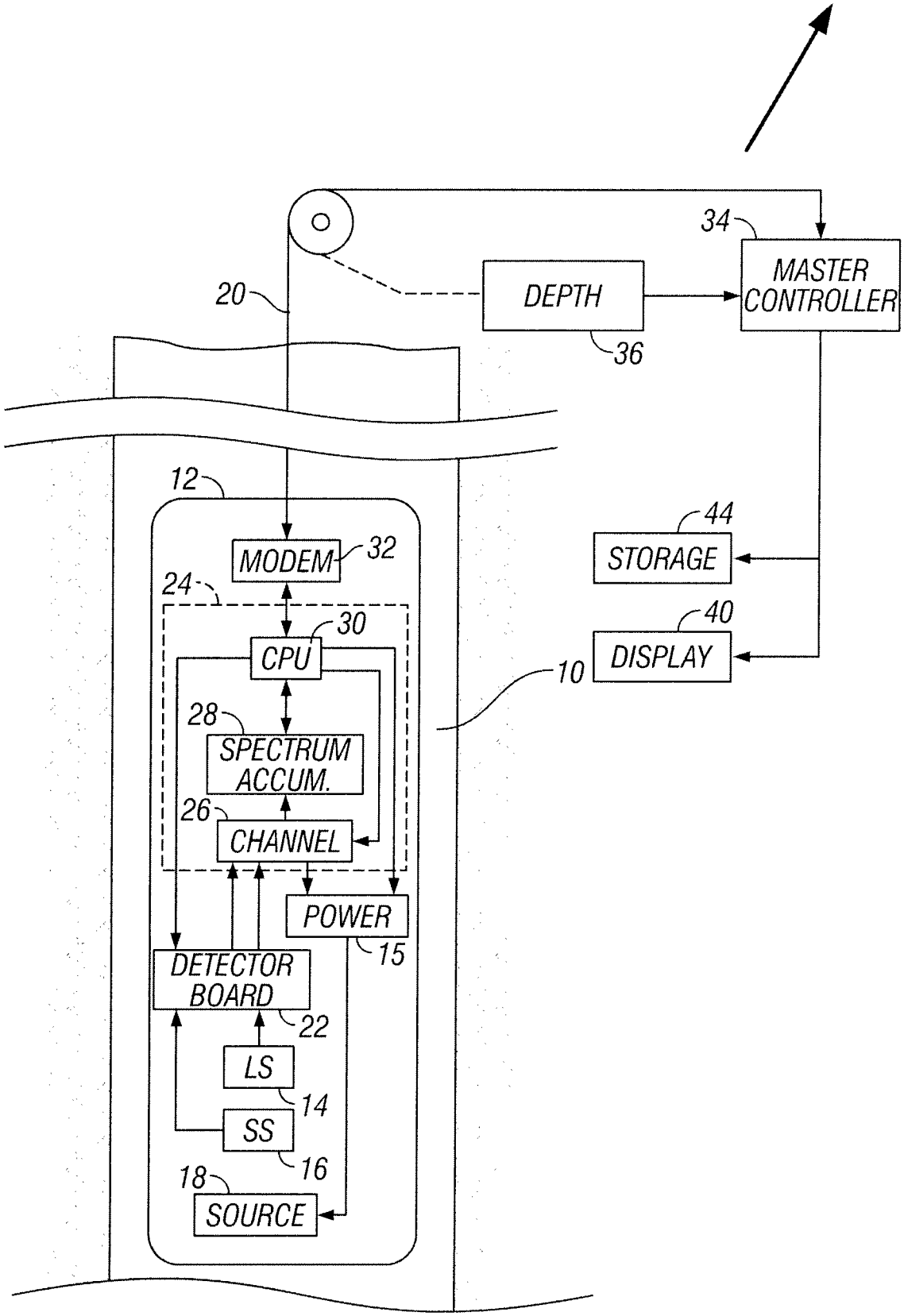

FIG. 1
(Prior Art)

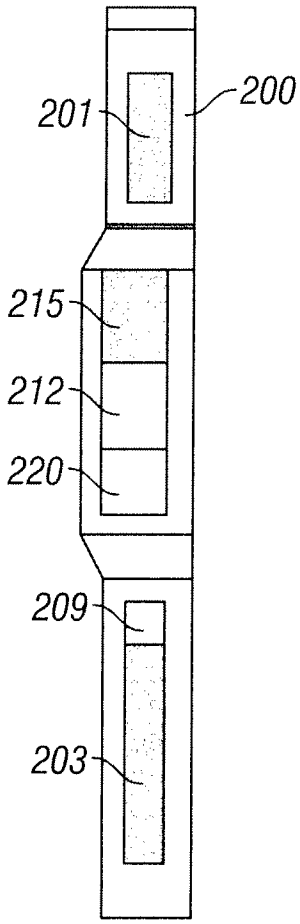

FIG. 2

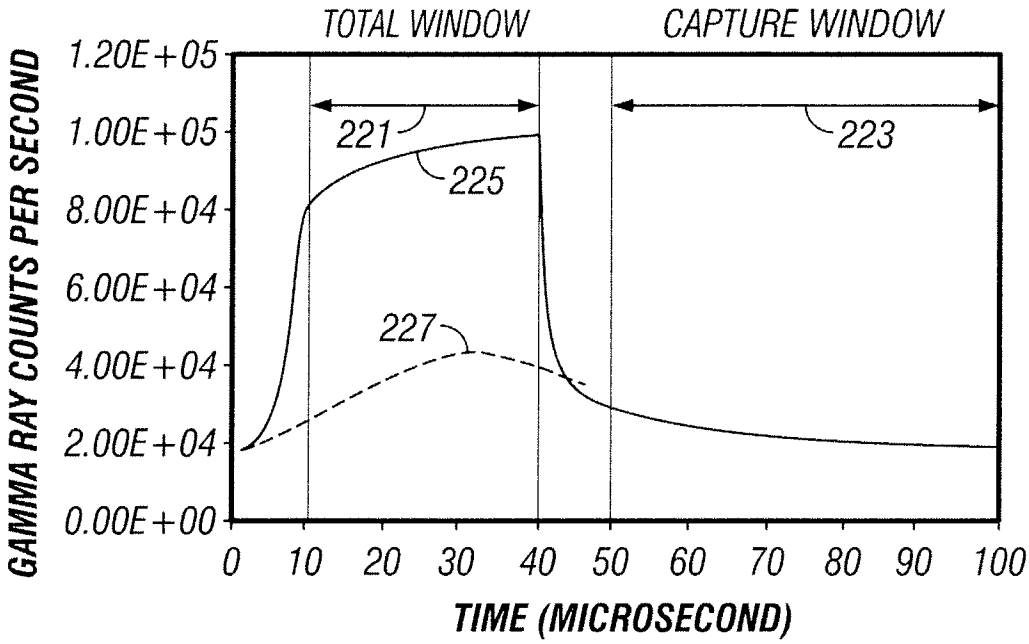
TOTAL WINDOW
CAPTURE WINDOW
GAMMA RAY COUNTS PER SECOND
1.20E+05
1.00E+05
8.00E+04
6.00E+04
4.00E+04
2.00E+04
0.00E+00
221
223
225
227
0
10
20
30
40
50
60
70
80
90
100
TIME (MICROSECOND)

FIG. 3

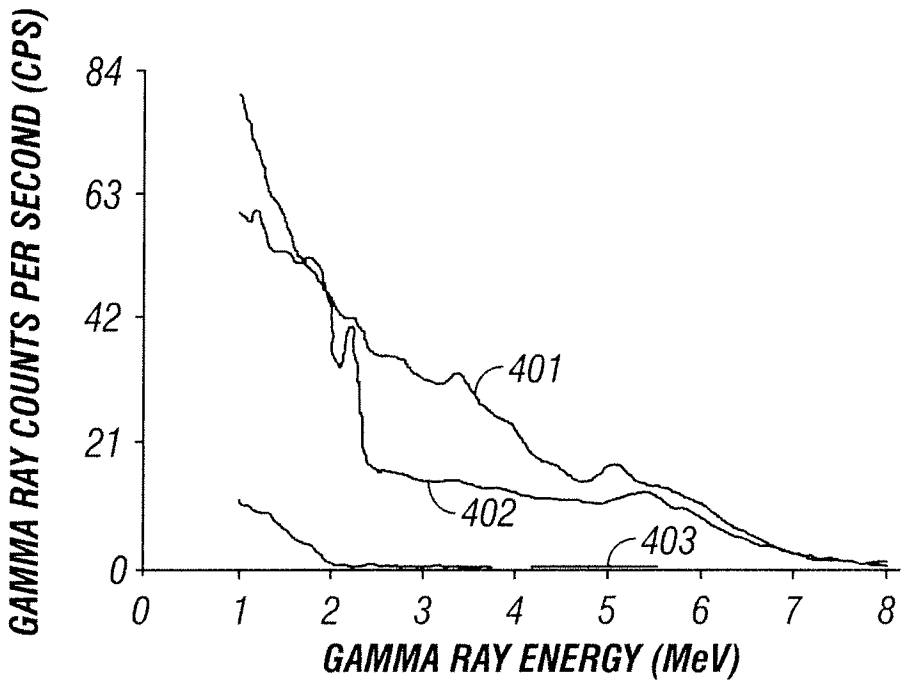
GAMMA RAY COUNTS PER SECOND (CPS)
84
63
42
21
0
401
402
403
0
1
2
3
4
5
6
7
8
GAMMA RAY ENERGY (MeV)

FIG. 4

TAR SAND EXAMPLES-FIELD LOG

WEIGHT FRACTIONS	WEIGHT FRACTIONS	WEIGHT FRACTIONS	WEIGHT FRACTIONS
SILICON	MAGNESIUM	ALUMINUM	CARBON
CALCIUM	IRON	SULFUR	TITANIUM
SILICON [wfsi] 0 0.5	MAGNESIUM [wfmg] 0 0.25	ALUMINUM [wfal] 0 0.25	CARBON [wfc] 0 0.25
(1) CALCIUM [wfca] 0.5 0	(1) IRON [wffe] 0.25 0	(1) SULFUR [wfs] 0.25 0	(1) TITANIUM [wfti] 0.1 0
(1)	(1)	(1)	(1)

FIG. 5

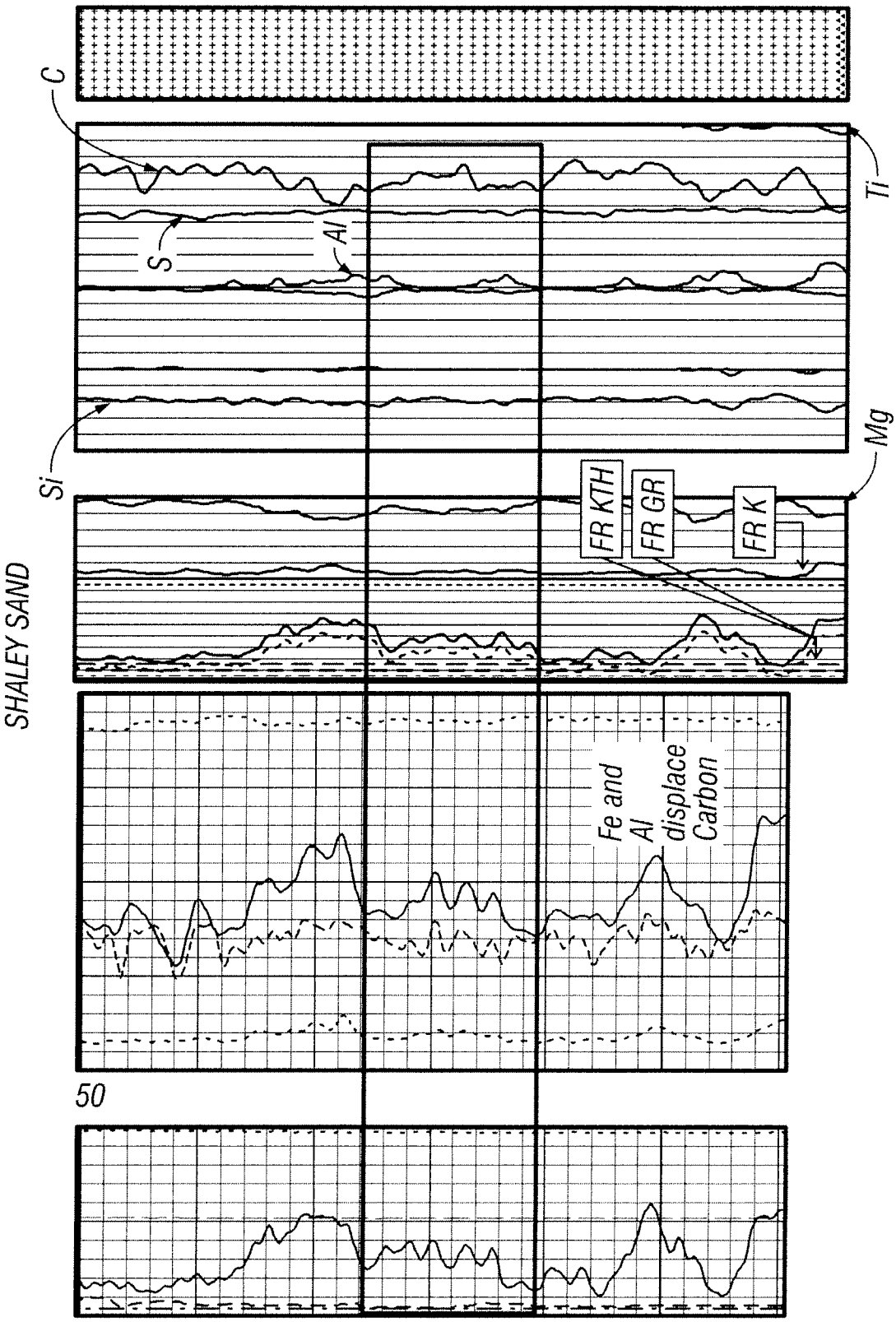
C
S
Al
Ti
Si
Mg
FR KTH
FR GR
FR K
SHALEY SAND
Fe and Al displace Carbon
50

FIG. 6

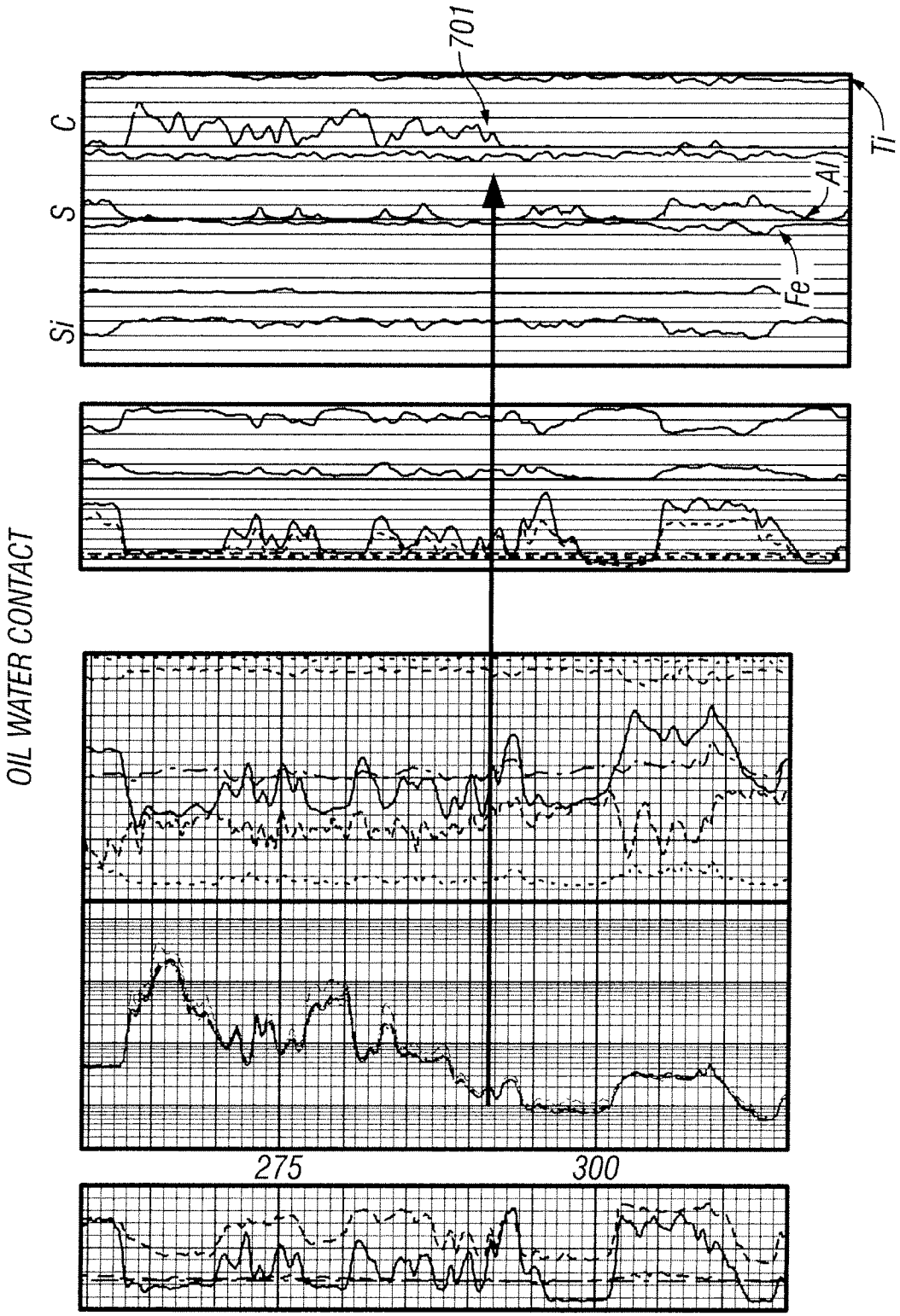

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 08/66726

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01V 5/10 (2008.04)
USPC - 250/269.6
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 250/269.6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 166/250.02; 250269.1; 702/8 (text searched)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST(USPT,PGPB,EPAB,JPAB); Google Scholar
Search Terms - borehole, viscosity, gamma ray, pulsed, neutron, spectrum, fluid

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0023626 A1 (Riley et al.) 01 February 2007 (01.02.2007), entire document, especially para [0002], [0012], and [0036]	1-16
Y	US 6,176,323 B1 (Weirich et al.) 23 January 2001 (23.01.2001), entire document, especially Abstract	1-16
Y	US 2006/0033022 A1 (Madigan et al.) 16 February 2006 (16.02.2006), entire document, especially para [0038]	5 and 12

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 August 2008 (21.08.2008)	29 AUG 2008
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774