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Methods and processes for determining the lithology as well as the mineralogy of subterranean formations is described. According to the methods and processes, well log data measurements (12) from pulsed neutron spectroscopy applications and associated
(57) **Abstract (continued):**
tool response parameters are solved using an expert system, which in turn generates an appropriate discriminator and estimates both general (14A) and specific (14B) lithology and mineralogy (16) constraints of the subterranean formation being analyzed. The methods exhibit good elemental correlation between conventional methods of lithology and mineralogy determination, and can provide numerous output data, including grain density and porosity data within zones of the formation.
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TITLE OF THE INVENTION

METHODS FOR QUANTITATIVE LITHOLOGICAL AND MINERALOGICAL EVALUATION OF SUBSURFACE FORMATIONS

BACKGROUND OF THE INVENTION

Field Of The Invention. This disclosure relates generally to methods for determining the lithology and mineralogy of a subterranean formation, and more particularly, to methods for determining the general lithology, specific lithology and mineralogy of a subterranean formation using expert systems and well log data.

Description Of The Related Art.

There has long been a need for open-hole logging tools and methods that would be capable of providing measurements of the lithology and mineralogy of a geologic formation in selected directions, providing measurements of the both the mineralogy and lithology both close to the bore hole and deep into the subterranean formation, and provide all such measurements with high vertical and lateral resolution. Quantitative information about the reservoir rock lithology and associated minerals is important not only for determining the producing potential for a specific formation, but for making technical and business decisions in hydrocarbon exploration and exploitation as well. For example, exploration geologists can use
rock mineralogy information associated with subterranean formations to reduce the
risk in discovering hydrocarbons by determining the thermal and diagenetic history of
the specific formation, defining the provenance (source area) and the depositional
environments of the sediments in the formation, and correlating certain minerals with
well logs. Formation mineralogy information can also be used during the exploration
process to assess reservoir quality, develop effective depletion strategies, and predict
the effect of rock-fluid interactions, while during the production process it can be used
to design work-over and completion strategies, such as selection of drilling fluids and
proper stimulation methods (e.g., effective acidizing or fracturing applications).

The interpretation of formation lithology, both general and specific, is also
important. For example, quantitative knowledge of the lithological constituents
present in a subterranean formation surrounding a well, as a function of depth, could
be valuable in assessing all aspects of exploration, evaluation, production and
completion. For example, suitable applications could include regional studies of
facies architectures, estimating distributions of reservoir facies, establishing quantities
of clay materials in all layers, identifying subtle and pronounced changes in
depositional or diagenetic facies by characterizing the formation minerals, and
planning enhanced recovery strategies.

Traditional methods of determining subterranean formation lithology and
mineralogy have used cores from wellbores, which are often analyzed using X-ray
diffraction techniques and the like. However, such traditional methods are very time-
consuming, and are not efficient for use in exploration applications. Consequently,
through the use of a variety of logging tools, numerous attempts to estimate, evaluate,
and interpret both the lithologies and the mineralogy of subsurface formations by
transforming log data into lithology and/or mineralogy logs have been made.

For example, methods have been suggested for the in situ examination of
subsurface formations penetrated by a borehole in order to ascertain the cation
exchange capacity of such formations within select geological regions. Using natural
gamma ray logging, signals were developed that functionally relate to the total
gamma radiation and to the potassium, uranium and thorium energy-band radiations.
According to these methods, the cation exchange capacities of core samples can be
determined by correlation with selected parameters provided by the gamma ray
spectrometer to establish functional relationships. Cation-exchange capacities of
formations in subsequent boreholes within the same and surrounding regions can then
be determined in situ by use of the natural gamma ray spectrometer and these established relationships. This technique is of seemingly limited utility, however, because cation-exchange capacity is being reportedly correlated to elements that generally have very little global relation to clay or other similar minerals that dictate cation-exchange capacity.

Other methods described in the art provide for quantifying and characterizing mineral content of a subterranean formation as a function of well depth. According to these methods, elemental data derived from logging tools can be input into an element-mineral transform mathematical operation, such as a matrix of the type constructed using multivariate statistical analysis methods, in order to determine the quantity of at least one or more of the dominant minerals within in the formation under evaluation. From both the mineral quantity information and the elemental log data, the formation minerals can be predicted or hypothesized. Other related methods and associated apparatus suggest methods and apparatus for determining formation lithology using gamma ray spectroscopy, using inelastic scattering gamma ray spectra taken in a borehole and analyzed by a least squares spectral fitting process to determine the relative elemental contributions thereto of chemical elements postulated to be present in unknown earth formations and contributing to the measured spectra from the formations. In some reports, based on the calibrated inelastic yields for selected elements, calibrated estimates of the elemental yields from measured thermal neutron capture gamma ray spectra may also be determined, from which further information concerning formation lithology may be derived or theorized.

More recently, several methods for quantifying the lithologic composition of formations surrounding boreholes have been suggested. Such methods typically involve the construction of two or more lithology compositional models from known well log data for a formation, and the subsequent combination of the models in order to determine a range of possible solutions having an upper limit defined by a pure component model and a lower limit defined by a proportional mixture model, thus allowing the maximum concentration of any lithologic component to vary between 0% and 100%.

Other reports directed to the estimation of mineralogy have been reported by Harvey, et al. [SPWLA 33rd Annual Logging Symposium, pp. 1-18 (1992); and Core-Log Integration, Geological Society (London), Vol. 136: pp. 25-38 (1998)], as well as by Hertzog, et al. [Society of Petroleum Engineers. SPE paper No. 16792, pp. 447-
460 (1987); SPE Formation Evaluation, Vol. 4, pp. 153-162 (1989)]. Several of these techniques describe the use of pulsed neutron devices, direct activation of the formation, and the natural gamma spectra of the formation, for use in obtaining continuous well logs of the major element chemistry of a formation. These tools and methods offer measurements of Si, Al, Ti, Fe, Ca, K, S and the minor elements Gd, Th and U, together with H and Cl. Transformation of the major elements into the more conventional oxide forms provides virtually complete major element oxide analysis at each measured depth interval down the borehole. However, the transformation of a rock's elemental composition to mineral and lithological assemblages has been the subject of numerous approaches, ranging from linear programming and genetic algorithms to numerical models such as least squares minimization.

For example, element to mineral transformation algorithms, used for quantifying minerals from downhole nuclear spectroscopy elemental data, have had limited success in representing the bulk chemical composition of a rock in terms of its mineralogy. More specifically, because the minerals of rock matrices contain many of the same elements in their crystal structures, quantification-type methods for determining minerals in subterranean rock formations, e.g., silicate minerals, using only chemistry or chemistry-based methodologies, without an a priori knowledge of the minerals present, can result in problems involving non-unique solutions resulting from compositional colinearity [see, Harvey, P.K., et al., Developments in Physics, Vol. 122: pp. 141-157 (1997); and, Lofts, J.C., et al., Nuclear Physics, Vol. 8: pp. 135-148 (1994)]. This challenge can in turn result in a poor estimate of those phases having similar compositions, which then in turn lead to errors in quantifying other phases in the rock, a problem which magnifies exponentially for each quantification process. In particular, element-to-mineral transformations using traditional, least squares methods and the like have been found susceptible to colinearity, rendering them substantially unreliable for mineral quantification [Chakrabarty, T., et al., J. Can. Petroleum Technology, Vol. 36: pp. 15-21 (1997)].

Further, many of the existing logging tools and methods, such as those described briefly herein, are unable to provide the adequate penetration into the geologic formation surrounding the borehole necessary to provide the requisite detailed geological information many well-log operators and analysts are looking for. In addition, many existing logging tools are not directional, and the resolution of
measurements is also limited, particularly at greater distances into the geologic formation. Further, and perhaps more importantly, existing methods for determining subterranean lithology and/or mineralogy are based on determining the mineralogy of the formation first, and then attempting to determine or correlate the lithology to the mineralogy. However, this is severely limiting, as errors in determining the mineralogy (such as errors that can occur in transforming the major elements into the more conventional oxide forms) can translate into significantly erroneous lithology characterizations.

This application for patent discloses methods for the determination of subterranean formation mineralogy from formation lithology data, using an artificial intelligence system which uses elemental measurements obtained from downhole tools comprising pulsed neutron devices to generate algorithms which can then be used to define the general lithology, then the specific lithology, and finally the mineralogy of a subterranean formation surrounding a wellbore or similar earth borehole.

BRIEF SUMMARY OF THE INVENTION

In an embodiment of the present invention, methods for determining the lithology of a formation surrounding an earth borehole are described, wherein the method comprises traversing the earth borehole with a well logging system comprising a neutron source; obtaining elemental concentration and elemental oxide data from the formation with the well logging system; generating a series of algorithms comprising the artificial intelligence system; generating a general lithology compositional model; and generating a specific lithology compositional model to determine formation lithologies from the compositional models. In accordance with aspects of this embodiment, the neutron source is an electronic pulsed neutron source, which can optionally further comprise a gamma ray source. In further accordance with aspects of this embodiment, the artificial intelligence system is selected from the group consisting of neural networks, genetic algorithm-based systems, fuzzy logic systems, cluster analysis systems, and combinations thereof.

In further accordance with aspects of this embodiment, the general lithology compositional model comprises determinants of sands, shales, carbonates (including both limestones and dolomites), evaporites, coal, and combinations thereof. In additional aspects of this embodiment, a specific lithology compositional model can
be generated, which can then be used to determine the specific lithology of a formation surrounding the earth borehole. Specific lithology which can be determined includes quartzose, feldspathic sand, lithic sand, shaley sand, limey quartzose, limey feldspathic sand, anhydritic limestone, calcic anhydrite, sandy shale, calcic shale, and combinations thereof.

In a further embodiment of the present invention, methods for determining the lithology and mineralogy of a formation surrounding an earth borehole are described, wherein the method comprises traversing the earth borehole with a well logging system comprising a neutron source; obtaining elemental concentration and elemental oxide data from the formation with the well logging system; generating a series of algorithms comprising an artificial intelligence system; generating a general lithology compositional model; generating a specific lithology compositional model; and determining the mineralogy of at least a portion of the formation surrounding the earth borehole from at least a portion of the compositional models. In accordance with aspects of this embodiment, the neutron source is an electronic pulsed neutron source, which can optionally further comprise a gamma ray source. In further accordance with aspects of this embodiment, the artificial intelligence system is selected from the group consisting of neural networks, genetic algorithm-based systems, fuzzy logic systems, cluster analysis systems, and combinations thereof.

In a further embodiment of the present invention, a process for producing hydrocarbon material from a subterranean formation is described, wherein the process comprises providing a wellbore extending through at least a portion of the subterranean formation; providing a conduit in fluid communication with a hydrocarbon producing zone within the subterranean formation; traversing the wellbore with a logging instrument; measuring at least one parameter of the subterranean formation surrounding the wellbore with the logging instrument; determining the general lithology of at least a portion of the subterranean formation surrounding the wellbore using an expert system; and producing a hydrocarbon fluid material from a producing zone of the subterranean formation surrounding the wellbore. In accordance with aspects of this embodiment, the logging instrument can comprise a pulsed neutron source, a gamma ray source, or a combination thereof. In further aspects of this embodiment, the general lithology determined comprises sands, shales, carbonates (dolostones and limestones), evaporites, coal, and combinations thereof.
Accordingly, in one aspect there is provided a method for estimating the lithology and mineralogy of a formation surrounding a borehole, the method comprising:

traversing the borehole with a well logging system on a logging tool string connected to surface equipment, the surface equipment including a computer and a processor coupled to one or more electromagnetic radiation systems or sources;

obtaining wellbore data from the formation with the well logging system;

sending the wellbore data to the processor;

generating a lithology compositional model by a process that includes converting the wellbore data to elemental data as major element oxides and then generating ternary diagrams from the elemental data; and

generating a complete quantitative mineralogy of the formation based on the lithology compositional model that has been generated;

wherein the generation of the compositional model and the quantitative mineralogy is done by the processor using data that is obtained from the well logging system; and

wherein the generation of the compositional model is performed by an artificial intelligence system.

In another aspect there is provided a method for estimating the lithology and mineralogy of a formation surrounding a borehole, the method comprising:

traversing the borehole with a well logging system on a logging tool string connected to surface equipment, the system including a computer and a processor coupled to one or more electromagnetic radiation systems or sources;

obtaining wellbore data from the formation with the well logging system on the tool string;

sending the wellbore data to the processor;

generating a general lithology compositional model by a process that includes converting the wellbore data to elemental data as major element oxides and then generating ternary diagrams from the elemental data; and

generating a quantitative mineralogy of the formation;

wherein the quantitative mineralogy is generated after the generation of the general lithology compositional model;

wherein the generation of the compositional model and the quantitative mineralogy is done by the processor using data that is obtained from the well logging system; and

wherein the generation of the compositional model is performed by an artificial intelligence system.

In yet another aspect there is provided an apparatus for making measurements of the lithology and mineralogy of an earth formation surrounding a borehole, the apparatus comprising:
(a) an electromagnetic radiation system which irradiates the earth formation surrounding at least a portion of the borehole and measures received radiation, the electromagnetic radiation system including at least one of:

(i) a neutron source and a neutron detector; and
(ii) a gamma-ray source and a gamma-ray detector; and

(b) a data processing system connected to the electromagnetic radiation system, the data processing system including a computer and a processor coupled to the electromagnetic radiation system;

wherein the processor comprises an artificial intelligence system that generates a lithology compositional model and a quantitative mineralogy of the formation based on the data received from the neutron detector or the gamma-ray detector;

wherein the lithology compositional model is generated before the quantitative mineralogy is generated, the lithology compositional model being generated by a process that includes converting the data received from the neutron detector or the gamma-ray detector to elemental data as major element oxides and then generating ternary diagrams from the elemental data using the artificial intelligence system; and

wherein the generation of the compositional model is performed by the artificial intelligence system within the processor.

In still yet another aspect there is provided a method for estimating the lithology and mineralogy of a formation surrounding a borehole, the method comprising:

traversing the borehole with a well logging system on a logging tool string connected to surface equipment, the system including a computer and a processor coupled to one or more electromagnetic radiation systems or sources;

obtaining wellbore data from the formation with the well logging system;

sending the wellbore data to the processor;

generating a general lithology compositional model;

generating a specific lithology compositional model; and

generating a quantitative mineralogy of the formation surrounding the borehole based on the general lithology, specific lithology, or both lithology compositional models that have been generated,

wherein the quantitative mineralogy is generated after the generation of the specific lithology compositional model;

wherein the generation of the compositional models is done by the processor using data that is obtained from the well logging system by a process that includes converting the wellbore data to elemental data as major element oxides and then generating ternary diagrams from the elemental data; and

wherein the generation of the compositional models is performed by an artificial intelligence system.
BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The file of this patent contains at least one drawing executed in color. Copies of this patent with color drawings will be provided by the Patent and Trademark Office upon request and payment of the necessary fee.

The following figures form part of the present specification and are included to further demonstrate certain aspects of the present invention. The invention may be better understood by reference to one or more of these figures in combination with the detailed description of specific embodiments presented herein.

FIG. 1 illustrates a well logging apparatus disposed in a wellbore penetrating earth formations.

FIG. 2A illustrates a general flowchart outlining methods for establishing the mineralogy of a subterranean formation.

FIG. 2B illustrates a flowchart showing details of the methods for establishing the mineralogy of a subterranean formation, illustrated in FIG. 2A.

FIG. 3 illustrates a ternary diagram showing the intersection of guidelines for normalized values of SiO₂, MgO, and CaO.

FIG. 4 illustrates a set of hybrid ternary diagrams used to develop an expert system for specific lithologies.

FIG. 5 illustrates a flow chart showing expert system logic for determining general lithology.

FIG. 6 illustrates a flow chart showing expert system logic to define specific sandstone lithologies.

FIG. 7 illustrates a flow chart showing expert system logic to define specific shale lithologies.

FIG. 8A illustrates a ternary diagram showing the intersection of guidelines for normalized values of S, CaO, and Fe₂O₃.

FIG. 8B illustrates a set of hybrid ternary diagrams used to develop an expert system for carbonate, anhydrite, and dolomite lithologies.

FIG. 9 illustrates a flow chart showing expert system logic to define carbonate lithologies.

FIG. 10 illustrates a flow chart showing the use of expert system logic to define evaporate lithologies.
FIG. 11 illustrates a schematic stratigraphic column for a section of the Johnson City (TX) test well formation, illustrating both the lithology and mineralogy of the stratigraphic units.

FIGS. 12A and 12B illustrate exemplary logic algorithms for the determination of mineralogy of a formation from the general and specific lithology information generated in accordance with aspects of the present disclosure.

FIG. 13 illustrates schematic stratigraphic column of the Western Louisiana test well of example 1, in comparison with core X-ray diffraction data from the same well.

FIG. 14 illustrates schematic stratigraphic column of the South American test well of example 2, in comparison with core X-ray diffraction data from the same well.

FIG. 15 illustrates schematic stratigraphic column of the West Texas Well of example 3, in comparison with core X-ray diffraction data from the same well.

While the inventions disclosed herein are susceptible to various modifications and alternative forms, only a few specific embodiments have been shown by way of example in the drawings and are described in detail below. The figures and detailed descriptions of these specific embodiments are not intended to limit the breadth or scope of the inventive concepts or the appended claims in any manner. Rather, the figures and detailed written descriptions are provided to illustrate the inventive concepts to a person of ordinary skill in the art and to enable such person to make and use the inventive concepts.

DETAILED DESCRIPTION

One or more illustrative embodiments incorporating the invention disclosed herein are presented below. Not all features of an actual implementation are described or shown in this application for the sake of clarity. It is understood that in the development of an actual embodiment incorporating the present invention, numerous implementation-specific decisions must be made to achieve the developer's goals, such as compliance with system-related, business-related, government-related and other constraints, which vary by implementation and from time to time. While a developer's efforts might be complex and time-consuming, such efforts would be, nevertheless, a routine undertaking for those of ordinary skill the art having benefit of this disclosure.
In general terms, Applicants have created processes and methods for determining the lithology and mineralogy of a subterranean formation surrounding a wellbore.

**ELEMENTAL INPUTS**

FIG. 1 shows a well logging apparatus 1 for use with the methods and process described in the present invention, wherein the well logging apparatus is disposed in a wellbore 2 drilled through earth formations 3A, 3B, 3C, and 3D in order to make measurements of properties of the earth formations 3A, 3B, 3C, and 3D. The wellbore 2 in FIG. 1 can be filled with a liquid suspension known in the art as “drilling mud”. A string of one or more logging tools 7, which can include a neutron apparatus as well as a plurality of additional logging tools or sondes, is typically lowered into the wellbore 2 by means of an armored electrical cable 8. The cable 8 can be spooled and unspooled from a winch or drum of any type known in the art. The tool string 7 can be electrically connected to surface equipment 4 by an insulated electrical conductor (not shown in FIG. 1) forming part of the cable 8. The surface equipment 4 can include one part of a telemetry system 5 for communicating control signals and data between the tool string 7 and a computer 6. The computer 6 can also include a data recorder 9 for recording measurements made by the apparatus and transmitted to the surface equipment 4. In accordance with aspects of the present invention, the logging tool 7 preferably comprises a pulsed neutron source, such as known in the art. In further aspects of the present invention, the logging tool 7 further comprises an elemental gamma ray detector capable of measuring capture gamma radiation, inelastic gamma radiation, natural gamma radiation, and combinations thereof. Suitable well logging tools for use in the methods of the present invention and for providing elemental concentration and/or elemental oxide data about the formation surrounding the wellbore (equivalently referred to herein as an earth borehole) include those described, for example, in U.S. Patent No. 7,205,535, entitled “Elemental Gamma Ray Signature Instrument”; and U.S. Patent No. 7,402,797, entitled “Method and Apparatus for Determining Aluminum Concentration in Earth Formations”.

Turning now to FIG. 2A, an overall process flow diagram for the methods of the present invention is illustrated. As shown therein, and in accordance with an embodiment of the present invention, the overall process 10 for quantitatively
determining the lithology of a subterranean formation having a wellbore extending therethrough comprises obtaining log data for a subterranean formation to be analyzed 12, determining the lithology of the subterranean formation 14, and then generating output and data 18 which described the lithology of at least a portion of the subterranean formation surrounding the wellbore. As further illustrated within FIG. 2A, the method can further comprise the process of determining the mineralogy of the subterranean formation 16 based on the lithology information that has been determined, and then generating output and data 18 useful in understanding both the mineralogy and lithology within the subterranean formation surrounding the wellbore. This may be especially useful in and around wellbores penetrating through a subterranean formation, for use in producing hydrocarbons. According to the methods and processes of the present invention, the determination of the lithology (including both the general lithology and/or the specific lithology of a formation) and the mineralogy of a subterranean formation are accomplished using an expert system (20), as will be discussed in more detail herein.

FIG. 2B illustrates a flow chart of a further embodiment of the present disclosure, wherein log data 12 is obtained from at least a section of the subterranean formation surrounding the wellbore or borehole. This log data is converted to elemental data which is presented as major element oxides and element information and is then fed to expert system 20, which generates ternary diagrams 13, providing this information in analog or graphical form, as desired. A series of algorithms, using the expert system 20, are then developed from the ternary diagrams. As will be discussed in more detail herein, such ternary diagrams that are generated can be standard ternary diagrams capable of segregating different lithologies from one another, such as those described by Pettijohn, et al. [USGS Professional Paper 440-S, p. 19 (1963)], or hybrid ternary diagrams, both of which can then in turn be used to further develop the expert system 20 for use in determining the general lithology 14a, as well as the specific lithology 14b of the formation. As further illustrated within FIG. 2B, upon determination of either the general lithology, the specific lithology, or both, the geochemical information can be generated as output data 18. Such output data 18 can be in any appropriate format, including lithology vs. depth plots, general lithology vs. depth plots, specific lithology vs. depth plots, mineralogy vs. depth plots, ternary diagrams, modified ternary diagrams, hybrid ternary diagrams and diagram sets, and bivariate (X-Y) plots, as well as combinations or modifications of such
output formats. An example of an exemplary combination output plot will be discussed in reference to FIG. 11 herein.

In accordance with the methods of the present invention, the methods of the present invention can further comprise obtaining additional logging data 11 from both geochemical logs and conventional well logs, in order to generally identify and quantify minerals in sedimentary rocks. As illustrated in FIG. 2B, this additional logging data 11 can be then be used, in combination with the general and specific lithology information (14a and 14b) to determine the mineralogy 16 of at least a portion of the subterranean formation surrounding the wellbore. Optionally, and equivalently, additional wellbore cuttings, core data, or logging data 11 can be used to enhance and better determine the general lithology, the specific lithology, or both, which can then be directly converted to lithology-based output data 18.

Types of additional data (11) include but are not limited to core data (such as X-ray diffraction data) and core cutting data, as well as well log data obtained from carbon/oxygen (C/O) logging (carbon/oxygen (C/O)) measurements, which allows the operator to monitor the reservoir through casing and tubulars in a time-lapse fashion over the life of the well independent of formation water salinity; sonic or acoustic measurements and the resultant data; resistivity (both shallow and deep) logging data; spontaneous potential (SP) logging data; photo-electric (PE) cross-section logging data; gamma ray (GR) logging data; high-definition induction logs (HDIL) and similar logs that measure resistivity, including open hole electric wireline tools; bulk density correction (ZCOR) data; compensated bulk density data (ZDEN); borehole-corrected compensated neutron porosity (CNC); micro-lateral resistivity (MLRL) data; nuclear magnetic resonance (NMR) logging techniques and data acquired from such techniques, including but not limited to magnetic resonance imaging logging (MRIL), density (\( \rho \)) NMR data, and NMR-derived clay bound water (CBW) volume determination and measurements; SpectraLog\textsuperscript{®} (K, U, Th) data, and similar spectral gamma ray tools and their resultant data; caliper (continuous recordation of well diameter, usually recorded in inches) measurement data, including DCAL (differential caliper) data; or combinations of two or more of these data sources.

Returning to FIG. 2B, having obtained log data 12 that provides elemental information of certain major elements, including but not limited to silicon, potassium, magnesium, calcium, carbon, iron, chlorine, titanium, thorium, manganese,
gadolinium, aluminum and sulfur, a computer system, which can be any suitable computer system known in the art, such as a standard human-machine interface (HMI), uses (check throughout) a series of algorithms based on the elemental data. These algorithms will be described in more detail below, but generally speaking these algorithms comprise the artificial intelligence system 20. As indicated previously, the artificial intelligence systems suitable for use with the present invention include, but are not limited to, expert system, neural networks, genetic algorithm-based systems, fuzzy logic systems, cluster analysis systems, and systems that are a combination of two or more of these systems. Utilizing the weight percent of major element oxides and elements, the artificial intelligence system 20 generates ternary discrimination diagrams 13, such as those described in the art by H. Rollinson [Using Geochemical Data: Evaluation, Presentation, Interpretation; John Wiley, Hoboken, NJ: 1993]. These ternary discrimination diagrams 13 can comprise standard ternary diagrams which illustrate relationships between selected elements based on their contribution to the observed mineral assemblage and to their modal abundance, as known in the art, as well as sets of hybrid ternary diagrams, as illustrated in FIGS. 4 and 8B herein. Having generated a series of appropriate ternary diagrams, the artificial intelligence system 20 then generates a general lithology compositional model 14a, using a series of logic flow diagrams as will be discussed in more detail below. At this point, at the discretion of the user, the system 20 can provide the general lithology compositional information about the subterranean formation surrounding the wellbore as output data 18, in an appropriate format, such as a general lithology vs. depth plot. Otherwise, the artificial intelligence system 20 proceeds to generate a specific lithology compositional model 14b, using a series of logic flow diagrams that are based upon the general lithology compositional model that has been generated. This specific lithology compositional model, and the associated information, can be provided as output data 18 in an appropriate format, such as a specific lithology vs. depth plot, or, equally acceptable, the information from the specific lithology compositional model can be used to generate a mineralogy compositional model 16. In this instance, using a combination of both the general and specific lithology compositional models, the artificial intelligence system 20 can proceed to generate a mineralogy compositional model 16 of at least a portion of the subterranean formation surrounding the wellbore. The system 20 may then convert the compositional model into appropriately formatted output data 18, such as a mineralogy vs. depth plot or similar output format.
In accordance with aspects described previously in reference to FIG. 2A, additional data 11 from other logging devices or logging information sources, such as NMR well-log data or SpectraLog®, SpectraLog™ II, data may optionally be integrated in the system 20 to further refine the general lithology compositional model 14a, the specific lithology compositional model 14b, the mineralogy compositional model 16, all three compositional models, or combinations of these models.

ARTIFICIAL INTELLIGENCE SYSTEM

The artificial intelligence system (AIS), referred to herein generally as expert system 20, is used in association with the present invention for a plurality of geochemical analysis functions, including but not limited to generating graphical or other presentations of ternary, hybrid ternary diagrams, and bivariate plots/diagrams, as will be described in more detail herein, as well as in using chemistry information and chemical ratios based on elemental information from well logging tools to establish the general lithology, specific lithology, and the mineralogy of the rock surrounding a wellbore extending into a subterranean formation.

As used herein, artificial intelligence system includes but is not limited to expert systems, neural networks, genetic algorithms, fuzzy logic systems, fuzzy neural networks, and cluster analysis systems, as well as combinations of two or more such systems interacting. Such artificial intelligence systems include any system capable of the acquisition and analysis of well log data. More specifically, the artificial intelligence system 20 can develop one or more algorithms from normalized ratios between elemental information, such as elemental oxide information, as provided by the well logging tool. This information may then be plotted on ternary diagrams, which are in turn used for delineating and determining general lithologies. The general lithologies which can be delineated and thus determined using this methodology include sands, carbonates, anhydrites, coal, and shales, as will be described in more detail herein. Additional algorithms, further developed from well log data such as elemental oxide ratios, e.g., ratios including ratios between two or more of K₂O, MgO, Fe₂O₃, as well as elemental determinates (such as the magnesium oxide and calcium oxide ternary values, MgT and CaT, respectively, and elemental concentration per unit weight values) and specific discriminators, obtained from elemental and chemical information plotted on ternary diagrams or hybrid ternary.
diagrams, allows the general lithology classifications to be narrowed to determine the specific lithologies.

The expert system 20 used herein and useful in generating the algorithms used to define the general lithology, specific lithology, and/or mineralogy of a rock can be written or modeled in any number of known computer programming languages or systems, including neural networks and VisualBasic (MicroSoft®). Other normative lithological and mineralogical computer programming approaches that have been used for rock analyses and are generally suitable for use in association with the present invention include three generally-known modeling approaches, or modified versions of such modeling programs. Two such suitable modeling approaches, represented by SEDNORM [Cohen and Ward, 1991; Computers and Geoscience, v. 17, p. 1235-1253], LPNORM [De Caritat, et al., 1994; Computers and Geoscience, v. 20, p. 313-347], and the modeling system MODAN [Paktunc, 1998; Computers and Geoscience, v. 24, p. 425-431], use a best-fit solution to a series of linear equations. Additionally, the systems 20 used herein may be divided into at least one central data processing facility and one or more remote and/or local user facilities, typically linked by encrypted network connections or similar links. The architecture of system 20 may be based on a shared processing functionality between remote or local user facilities and a central location, such as a company centralized location. The remote or local user facilities may also include a Web user or Internet user who requests information or interacts with the system 20.

As used herein, the term "neural network" refers to a type of artificial intelligence that attempts to imitate the way a human brain works and functions. Rather than using a digital model, in which all computations manipulate zeros and ones, a neural network works by creating connections between processing elements. Neural networks may be particularly effective in predicting and generating compositional algorithms and models when the network has a large database of prior examples or data point values to draw upon. While a neural network may imply a non-digital computer, in accordance with the present invention, neural networks may also be simulated on digital computers, as known in the art.

Similarly, as used herein, the term "expert system" broadly refers to computer applications and systems capable of performing tasks that would otherwise be performed by a human expert. Some expert systems are designed to take the place of human experts, while others are designed to aid them, both of which are contemplated.
by the present invention. Expert systems are part of a general category of computer applications known as artificial intelligence, as suggested above. Expert systems are meant to solve real problems which normally would require a specialized human expert (such as a doctor or a mineralogist). Building an expert system therefore first involves extracting the relevant knowledge from the human expert. Such knowledge is often heuristic in nature, based on useful "rules of thumb" rather than absolute certainties. Extracting it from the expert in a way that can be used by a computer is generally a difficult task, requiring its own expertise. A knowledge engineer has the job of extracting this knowledge and building the expert system knowledge base.

Expert systems in accordance with the present invention may be of any type, especially those which are iterative in nature, in that they were developed from and written in a manner which facilitates easy inspection and modification. Such systems will be able to explain their reasoning (to expert, user and knowledge engineer) and answer questions about the solution process. Such expert systems will also be capable of being readily updatable, without having to rewriting large portions of code; rather, the systems will be capable of adding or deleting localized chunks of knowledge.

The most widely used knowledge representation scheme for expert systems is rules (sometimes in combination with frame systems). Typically, the rules won't have certain conclusions—there will just be some degree of certainty that the conclusion will hold if the conditions hold. Statistical techniques may also be used by expert systems herein, in order to determine such certainties, and/or to generate and define algorithms. Rule-based systems, with or without certainties, are generally easily modifiable and make it easy to provide reasonably helpful traces of the system's reasoning.

As described briefly above, the expert system 20 uses algorithms or a series of algorithms for use in determining the general lithology, specific lithology and mineralogy of a rock or rock formation, but can also be used to develop and generate the ternary diagrams that act as the primary vehicle for lithology and mineralogy model development. Generally, the expert system utilizes the weight percent of major element oxides—specifically, SiO₂, K₂O, MgO, CaO, Fe₂O₃, Al₂O₃, and S—plotted on ternary discrimination diagrams to distinguish between siliciclastic, evaporitic, and carbonate lithologies, among others. In accordance with one aspect of the present invention, aluminum elemental data is not emphasized in accordance with the
methods described herein. However, its use and inclusion in lithology and mineralogy discrimination determinations can be contemplated in specific instances.

In example of the utility of the ternary diagram, and owing to the importance of the ternary diagram in developing the models for use with the methods of the present invention, a brief explanation of their use, as well as their expansion into hybrid ternary diagrams, is now provided. In example, elemental percentages of a rock having a given composition of about 5% CaO, about 4% MgO, and about 80% SiO2 will be normalized using the expert system 20, and then plotted on a ternary diagram, chemical discriminatory diagram, or a similar type of diagram. The exemplary normalizations for this example are as follows:

\[
\text{CaO} \% = 6\% = \frac{\text{CaO}}{\Sigma (\text{CaO}, \text{MgO}, \text{SiO}_2)} \times 100
\]
\[
\text{MgO} \% = 4\% = \frac{\text{MgO}}{\Sigma (\text{CaO}, \text{MgO}, \text{SiO}_2)} \times 100
\]
\[
\text{SiO}_2 \% = 90\% = \frac{\text{SiO}_2}{\Sigma (\text{CaO}, \text{MgO}, \text{SiO}_2)} \times 100
\]

The position of this point is then plotted on a standard ternary diagram based on the three variables denoted by the intersection of the mark '*' on FIG. 3. According to the point defined by this relationship, the expert system would generate the ternary diagram (or equivalent) and plot the above chemistry in the zone shown on the ternary diagram as a "sandstone".

Referring to FIG. 3 in more detail, the zones outlined on the general ternary illustrates the range of compositions for different lithologies that can be identified using this approach. The zones outlined on the ternary illustrate the range of compositions for different lithologies that can be identified using this approach. Near the SiO2 apex 26 of the ternary, for example, sandstones can be outlined. Between SiO2 and CaO, sandstones having variable amounts of carbonate content can be identified, while limestone compositions can be determined near the CaO apex along with the silicon content. CaO and MgO can be used to identify dolomite, and points between the dolomite composition and CaO can be used to define the relative proportion of calcite versus dolomite in a carbonate. In addition, ratios between SiO2 and MgO + Fe2O3 can be used in further defining shale lithology, as described in more detail below.

FIG. 4 illustrates an exemplary hybrid ternary diagram for use by the expert system of the present invention in determining the specific lithology of rock formations. Studies of chemistry and quantitative mineralogy information from lithic,
feldspathic, and quartzose sandstones have led to the conclusion that the Fe$_2$O$_3$ and K$_2$O ratio versus the actual SiO$_2$ value of the rock is applicable for discriminating between specific siliciclastic lithologies, as has been supported by the work of Moore, et al. [J. Sedimentary Petrology, vol. 40: pp. 1147-1152 (1970)] and Wendlandt, et al. [American Association of Petroleum Geologist Bulletin, vol. 74: pp. 837-856 (1990)]. However, due to difficulties associated with exploring such detailed relationships with a standard ternary diagram due to normalization of values resulting in loss of resolution over the detailed chemistry of the rock, hybrid ternaries such as the hybrid ternary group 30 illustrated in FIG. 4 were developed for use in association with the present invention. The hybrid ternary groups 30 illustrated in FIG. 4 use the normalized ratio between Fe$_2$O$_3$ and K$_2$O versus the actual silicon or calcium content (determined as their oxides) in order to determine the specific lithology of sandstones. Using this approach, and looking specifically at plot A in FIG. 4, quartzose 32 can be clearly distinguished from dolomites 31 and carbonates 33. Similarly, looking at plot C, quartzose 32 can also be clearly distinguished from feldspathic sandstones 34 and lithic sandstones 36. The bottom normalized ratio between K$_2$O and MgO of plot B versus the actual silicon (SiO$_2$) content allows for the determination of carbonates 33, and their distinction from feldspathic sandstones 34 and lithic sandstones 36. Turning to the central hybrid ternary diagrams C and D of FIG. 4, the normalized ratio between K$_2$O and SiO$_2$ versus either Fe$_2$O$_3$ (diagram C) or MgO (diagram D) is illustrated. As illustrated in diagram C, the hybrid diagram allows for the differentiation of shales that are iron rich (35) from shales that are magnesium rich (38), while diagram D illustrates the determination of magnesium-rich shale (38) from dolomites (31). Finally, in the third set of hybrid ternary diagrams, referring specifically to diagrams E and F, feldspathic sandstones 34, carbonates 33, dolomites 31, and limey sandstones 37 can be differentiated by plotting a normalized ratio of K$_2$O and either MgO or Fe$_2$O$_3$ versus the actual calcium oxide (CaO) content. For example, in diagram E, feldspathic sandstones 34 can be distinguished from limey sandstones 37 and carbonates 33, while in diagram F, dolomites 31, carbonates 33, feldspathic sandstones 34, and limey sandstones 37 can all be clearly distinguished. In this manner, the sandstones can be discriminated, using the expert system and methods of the present invention, into quartzose, feldspathic, and lithic sandstone specific lithology classifications.
Using both general and hybrid ternary diagrams, the expert system can be further developed for use in distinguishing between various lithologies, and thereby allowing for the determination of both the general lithology and specific lithology of a rock formation surrounding a wellbore, as well as for determining the mineralogy of a rock formation surrounding a wellbore.

**LITHOLOGY DETERMINATION**

The present disclosure is directed generally to the use of wellbore data to determine the lithology and mineralogy of formations surrounding a subterranean borehole. In this regard, the meaning of the terms "mineralogy" and "lithology", as well as the characteristics of these descriptors of rocks, is necessarily outlined for the purposes of the present disclosure. Minerals are known to be naturally occurring homogeneous inorganic solids, composed of one or more chemical elements whose internal orderly arrangement forms a geometric crystal lattice. The three main mechanisms of their formation are precipitation from solution, solidification due to cooling of magmas, and sublimation from vapor [Palache, C; Berman, H; and Frondel, C; The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana; 1951]. Differences in chemical bonding during formation from these processes produce minerals that possess definite physical and chemical properties. Several of the traits of notable importance in determining differences include, but are not limited to, cleavage, fracture, hardness, and specific gravity. "Cleavage," as used herein, refers to a physical trait of many minerals, and is a measure of the tendency of a mineral to break along planes of weak bonding. Conversely, "fracture", as used herein, refers to a physical property exhibited by minerals whose bonds are strong along all crystallographic planes [Dana, 1951, id.]. A term related to fracture, and often used in conjunction with the term fracture in classifying or describing minerals, is the term tenacity, which is the resistance that a mineral offers to breaking, crushing, bending, cutting, or other acts of destruction. Tenacity and fracture are related in that the "fracture" of a mineral (or rock) is how the mineral breaks once the tenacious limit has been exceeded. In example, quartz is the most abundant and hardest common mineral found in sedimentary rocks. Quartz exhibits "conchoidal fracture" [Dana, J. D.; A System of Mineralogy (6th Ed.): New York, Wiley; Rewritten by E. S. Dana (1915)]. An attempt to cleave this covalently-bonded mineral causes the crystal to shatter in a manner similar to glass. In contrast, the mineral "calcite" exhibits
rhombohedral cleavage in three directions, two of which are perpendicular to one another. Feldspars, common sedimentary minerals, also possess two directions of cleavage, oriented approximately 90° to each other.

Hardness and specific gravity are other important physical properties of minerals. Hardness is a measure of a mineral’s resistance to scratching or abrasion, usually represented on a scale ranging from 0 to 10, the scale being known as Moh’s relative hardness scale, while specific gravity (often abbreviated s.g.) is a comparison of a mineral (including metallic minerals) or rock material’s weight with the weight of an equal volume of water, and is measured in terms of grams per cubic centimeter, g/cc. As used herein, the term “specific gravity” is equivalent to the density of a mineral. Quartz, for example, has a relative scratch hardness (Mohs hardness = 7), substantially greater than that of calcite (Mohs hardness = 3) [Dana, J. D.; A System of Mineralogy (6th Ed.): New York, Wiley; Rewritten by E. S. Dana (1959)]. This would indicate that a quartz grain will survive abrasion during transport more readily than will calcite.

Sedimentary rocks, in contrast to pure minerals, consist of accumulations of minerals, either as grains or rock fragments, resulting from erosion, sedimentation, and precipitation which is associated with alluvial, fluvial, Aeolian and marine processes. The term “lithology” as related to these sedimentary rocks describes the physical attributes of the rock, including the grain size and texture of the minerals and fragments comprising the rock. Therefore, a “rock”, in contrast to a “mineral”, may be defined as a heterogeneous solid which is composed of one or more minerals whose mineral types, grain sizes, and textures determine its lithology. In the case of rocks composed of silicate minerals, or siliciclastics, the grain sizes and texture will define whether the rock is a shale, siltstone, or sandstone [Folk, R.L., in The Petrology of Sedimentary Rocks: Austin, TX, Hemphill Publishing Co., (1974)]. Carbonate lithologies, which are predominantly composed of calcite and dolomite, are also classified according to grain size [Dunham, R. J., “Classification of Carbonate Rocks According to Depositional Texture,” in Ham, W. E. ed., Classification of Carbonate Rocks: American Association of Petroleum Geologists Memoir 1, pp. 108-121 (1962)].

Minerals that compose lithologies, such as sandstones, can include bulk sand sized assemblages of quartz, feldspar, and mica with minor clay. Shales, on the other hand, are composed of predominately silt and clay sized minerals such as quartz and
feldspar with abundant clay minerals such as kaolinite, illite, and smectite. Carbonates can also include siliciclastic minerals and rock fragments along with other chemical mineral precipitants such as anhydrite and gypsum. These mineralogical generalizations however are complicated by the formation of other minerals through diagenesis and metasomatism within the matrix. Therefore, the term “shale” is not comparable to the term “clay mineral” used to describe illite, smectite or kaolinite, nor can “sandstone” be used as an equivalent term for minerals such as quartz, feldspars or other silicates. One term describes lithology while the other describes mineralogy.

These distinctions have not always been made clear in the well logging industry. Lithology and mineralogy terms have often been used interchangeably to describe the same entity, which can often lead to misinterpretations concerning the true meaning of the terms. For example, the usage of the lithology term “sand” and the mineral term “quartz” together for describing a rock is not compatible. A “sand” does not possess the physical traits as described previously for minerals, nor are the physical and chemical properties of “quartz” bounded by any grain size distinction inclusive of “sand”.

Consequently, in the current patent application, the terms “lithology”, and “specific lithology” are used to describe the chemistry associated with a composite mineral matrix. Similarly, the term “mineralogy”, as used herein, is meant to describe and quantify the minerals composing those lithology matrices. These distinctions are in sharp contrast to other current quantitative methods, wherein the chemistry is used to determine the quantitative lithology where individual silicate, carbonate and clay minerals are not segregated based on the chemistry, but instead are represented by assemblages of silicate, carbonate and clay groups.

As used herein, the term “general lithology” refers to the bulk lithology of a rock (a heterogeneous solid which is composed of one or more minerals), without regard to specific type. General lithologies that can be determined according to the methods of the present invention include, but are not limited to, sands (such as sandstones), shales, carbonates, coal, and evaporites. These general lithologies in turn can be used to determine the “specific lithology”, which as used herein refers to the more particular, definitive lithology of a formation. Sands include but are not limited to the specific lithologies quartzose sands (sands containing predominantly quartz, with minor quantities of other minerals), feldspathic sandstones, lithic sands, limey
sands, and shaley sands. Shales include sandy shale, magnesium-rich (Mg-rich) shale, and iron-rich (Fe-rich) shale. Carbonates include limestone and dolomites. Evaporites that can be determined include but are not limited to salts and anhydrites.

Referring now to FIG. 5, a flow diagram illustrating an expert system logic flow chart for determining the general lithologies of a subterranean formation is shown. With respect to this figure, and other figures described herein illustrating general flow diagrams, all elements that are listed refer to the elemental oxides (e.g., "Ca" means CaO), unless specified otherwise. The exceptions to this are the elements sulfur (S) and carbon (C), which as used herein refers to the element, and not the oxide. Additionally, in referring to the flow diagrams herein, it should be noted that the choice of values included are not necessarily limited, and that the choice of values for specific discriminators or elemental-oxide values can affect all of the other values throughout the system computations. That is, it should be realized that while changes can be made to values within the flow diagram of FIG. 5, these values may necessitate changes in the subsequent decision prompts and value computations throughout the analysis in order to obtain meaningful results.

Prior to the determination of the general lithologies as outlined in FIG. 5, and in order to more accurately differentiate between clay-containing and non-clay-containing lithologies, the expert system optionally first determines the amount of magnesium that is associated with clay, and not associated with carbonates, by comparing the amount of magnesium oxide with the amount of potassium oxide, using the ratio of potassium oxide-to-magnesium oxide (K/Mg) of K-feldspar/ilillite on the ternary diagram illustrated in FIG. 4. This value is assigned to the amount of magnesium oxide, MgO (represented herein by Mg*). Similarly, the expert system can also optionally and alternatively first determine the amount of iron oxide that is associated with clay and not associated with carbonates and other iron-oxides and iron-containing minerals. This is determined by a computational evaluation of the allowable ratio of potassium oxide-to-iron oxide (K2O/Fe2O3) of K-feldspar/chlorite. This value is assigned to Fe*.

Returning now to FIG. 5, a series of "if" and "then" statements coupled with percentages of certain elements from the ternary diagram and/or hybrid ternary diagram are presented, and initiate a path for sorting through the multitude of possible general lithology determination factors. In this flow chart, as well as others described herein, a siliciclastic discriminator, such as the SiO2/(SiO2 + K2O + Mg* + Fe*) ratio,
also designated as "SS", plays a significant role in directing the course of the methods and process. It should be noted, however, that while this siliciclastic discriminator is sometimes most useful in segregating siliciclastic sandstone lithologies versus carbonates (limestone and dolomite) and shales, the expert system used for the methods and processes described herein was developed with the possibility that the MgO and/or Fe₂O₃ chemistry of the rock formations may not all be attributed to silicate minerals. Consequently, in such instances, the primary general lithology ratio is adjusted according to the excess contributed by carbonate, oxide, and sulfide phases.

As an example of operation of FIG. 5 to determine the general lithology of a rock or subterranean rock formation, the expert system first differentiates between carbonates/anhydrites and sands and shales by evaluating the amount of calcium in the rock at decision prompt 44, which is determined from the CaO (Ca) value based on the ternary diagrams illustrated in FIG. 3 and FIG. 4. If the computed CaO (Ca) value is greater than α (wherein α ranges from about 10 wt. % to about 16 wt. %), shales, sands and coal are excluded and the magnesium oxide value (Mg, as determined from MgO in the ternary diagrams) will be used to distinguish the rock between a dolostone and an anhydrite or a limestone. At decision prompt 46, the magnesium oxide value (Mg) is computed by the expert system, and evaluated. If Mg is greater than β (wherein β ranges from about 5 wt. % to about 11 wt. %), then the system classifies the rock as a dolostone. If, however, Mg is computed and determined to be less than β, then the calcium oxide value (Ca) will be used to further evaluate the rock. At decision prompt 48, if the second calcium oxide value (Ca) is computed to be greater than α′, (wherein α′ ranges from about 15 wt. % to about 22 wt. %), then the system proceeds to decision prompt 50 to evaluate the elemental sulfur content (S) in order to further classify the rock's general lithology. If the computed value of S is greater than δ (wherein δ ranges from about 5 wt. % to about 23 wt. %, including about 11 wt. %), then the rock is determined to have the anhydrite general lithology. If the computed S is less than δ, however, then the magnesium content of the rock that is associated with limestone should be evaluated. At decision prompt 52, the expert system computes and evaluates the additive value of the calcium oxide content (Ca, based on the CaO ternary value) and the magnesium oxide from dolomite value (MgD). If the computed value of Ca + MgD is greater than λ
(wherein \( \lambda \) ranges from about 15 wt. % to about 40 wt. %), then the rock is found to have a limestone general lithology. If the computed value of \( \text{Ca + MgD} \) is determined to be less than \( \lambda \) at decision prompt 52, then the carbonate and anhydrite general lithologies are excluded, and the system must proceed to decision prompt 54 to determine whether the rock is a shale, a sandstone, or coal.

In continued reference to FIG. 5, if by computation and evaluation the expert system has excluded the carbonates and anhydrite general lithologies, the system then attempts to differentiate between coal, sand, and shale general lithologies. At decision prompt 54, the expert system computes and evaluates the silicon oxide value (Si) and the elemental carbon value (C). If the rock is determined to have a Si value less than \( \xi_1 \) (wherein \( \xi_1 \) ranges between 10 wt. % and 40 wt. %) and an elemental carbon value (C) greater than \( \theta \) (wherein \( \theta \) ranges between 40 wt. % and 100 wt. %), then the system classifies the rock as a coal. However, if either of these two requirements is not met, the system will use the ratio of \( \text{Si/(Si + Mg^* + K + Fe^*)} \) at decision prompt 56 to evaluate the general lithology of the rock formation. If the computed ratio of \( \text{Si/(Si + Mg^* + K + Fe^*)} \) is greater than \( \sigma \) (wherein \( \sigma \) ranges from about 0.6 to about 1.0), then the expert system determines that the rock has a sandstone general lithology. In contrast, if the ratio of \( \text{Si/(Si + Mg^* + K + Fe^*)} \) is computed to be less than \( \sigma \), then the rock is determined to be shale. In order to further differentiate the shale, at decision prompt 58 the system 20 computes and evaluate the magnesium oxide ternary value (MgT), in order to determine if the rock is a shale. If the MgT value has a computed value less than \( \beta_1 \) (wherein \( \beta_1 \) ranges from about 0.1 to about 0.4), then the rock is determined to be a shale; conversely, if the MgT is evaluated and by computation found to be greater than \( \beta_1 \), then the shale general lithology will be excluded, and the general lithology of the rock will be undetermined.

Once the general lithologies of a subterranean formation surrounding a wellbore have been determined, the data can be provided as output to a customer, as suggested above, or can be used to further generate a second compositional model which describes the specific geology of the subterranean formation surrounding the wellbore. Exemplary logic flow diagrams illustrative of the general processes for determining the specific lithology of a formation, as utilized by an expert system as described herein, are shown in FIGS 6-10.
FIG. 6 illustrates a flow chart showing expert system logic for determining specific lithology for sandstones. To differentiate between the different types of specific sandstone lithologies, the expert system first calculates the relative average weight percent (\(\xi\) %) of silicon oxide (Si) in the formation at decision prompt 60. If the relative average weight percent of silicon oxide is greater than \(\xi\) (wherein \(\xi\) ranges from about 70 wt. % to about 100 wt. %), then the system is determined to be a quartzose sandstone, and the lithic, feldspathic, and shaley sandstone specific lithologies are excluded from consideration. At the next decision prompt, decision prompt 62a, the expert system then computes and evaluates the Ca oxide ternary value (CaT), which is determined by the system using a CaO-SiO\(_2\)-MgO ternary diagram. If the CaT value is found to be greater than \(\alpha_1\) (wherein \(\alpha_1\) ranges from about 0.01 to about 0.15), then quartzose is excluded as an option, and the specific lithology of the rock is determined to be limey quartzose. Conversely, if at decision prompt 62a the CaT value is found to be less than \(\alpha_1\), then the rock is determined to be quartzose.

Continuing to refer to FIG. 6, if at decision prompt 60 the relative average weight percent (wt. %) of silicon oxide (Si) is less than \(\xi\), then quartzose is excluded from consideration in determining the specific lithology of the sandstone, and lithic, feldspathic, and shaley sandstones are considered by the system. At decision prompt 64, the system evaluates the ratio of Fe\(_2\)O\(_3\)/(K\(_2\)O + Fe\(_2\)O\(_3\)) [represented as the Fe\(^+\)/(K+Fe\(^+\)) ratio] and the siliciclastic discriminator (SS). If the ratio of Fe\(^+\)/(K+Fe\(^+\)) is greater than \(\psi\) (wherein \(\psi\) range from about 0.3 to about 0.7), and the siliciclastic discriminator (SS) value is less than \(\sigma_1\) (wherein \(\sigma_1\) ranges from about 0.85 to about 0.95), then the expert system classifies the rock as a lithic sandstone, and excludes feldspathic and shaley sandstones as potential specific lithologies. In this instance, the calcium oxide ternary value (CaT) is then evaluated by computation at decision point 62b; if CaT is found to be greater than \(\alpha_1\), then the expert system classifies the rock as limey lithic sandstone. If, however, the calcium oxide ternary value (CaT) at decision prompt 62b is found to be less than \(\alpha_1\), then the expert system classifies the rock as lithic sandstone. Following the flowchart of FIG. 6 and returning to decision prompt 64, if after computation and evaluation both requirements are not met, then the expert system proceeds to decision prompt 66. At decision prompt 66 the system evaluates the siliciclastic (sand-shale) discriminator (SS) to determine if it is greater than \(\sigma_2\) (wherein \(\sigma_2\) ranges from about 0.85 to about 0.95). The SS value is computed
and evaluated, and if found to be greater than $\alpha_2$, then the expert system classifies the rock as feldspathic sandstone, and proceeds to decision prompt 62c. If the CaT at decision prompt 62c is found to be greater than $\alpha_1$, after computation and evaluation, then the rock is classified as having a limey feldspathic sandstone; conversely, when CaT is less than $\alpha_1$ at decision prompt 62c, the rock is determined to have a feldspathic specific lithology. Alternatively, if SS is found to be less than $\alpha_2$, then feldspathic sandstones are excluded as a specific lithology, and the expert system classifies the sandstones as shaley sandstones and proceeds to decision prompt 62d. If the calcium oxide ternary value (CaT) at decision prompt 62d is found to be greater than $\alpha_1$, after computation and evaluation, then the rock is classified as having a limey shaley sand specific lithology; otherwise, when CaT is less than $\alpha_1$ at prompt 62d, the rock is classified as having a shaley sand specific lithology.

FIG. 7 illustrates a flow chart showing exemplary expert system logic for determining the specific lithology for shales, using an expert system in accordance with the present disclosure. As illustrated therein, having been determined by the expert system to have a general lithology classification of a shale, the elemental data from the rock is then further evaluated by the expert system to differentiate the various specific lithologies of shales—calcic shales, sandy shales, iron shales, and magnesium shales. In an example of operation, the system first evaluates the amount of calcium oxide (CaO) present in the rock at decision prompt 70. If the amount of CaO (Ca) is computed to be greater than $\alpha'$ (wherein $\alpha'$ ranges from about 10 wt. % to about 25 wt. %), then the sandy, iron-rich and magnesium-rich shales are excluded, and the rock is determined to have a calcic shale specific lithology. Conversely, if after computation and evaluation at decision prompt 70 the amount of calcium oxide is computed to not be greater than $\alpha$, then the expert system proceeds to evaluate the siliciclastic discriminator ratio (SS) value at decision prompt 72. If SS ratio value is computed to be greater than $\sigma_3$ (wherein $\sigma_3$ ranges from about 0.7 to about 1.0), then the rock is determined by the expert system to have a sandy shale specific lithology. If SS is less than $\sigma_3$, however, then the sandy shale specific lithology is excluded, and the expert system proceeds to decision prompt 74, where the ratio of iron oxide (Fe) to magnesium oxide (Mg), (Fe/Mg), is computed and evaluated. If the Fe/Mg ratio is a value greater than $\phi$ (wherein $\phi$ ranges from about 1.5 to about 8.0), then the expert system determines that the rock has an iron-rich shale specific lithology; if the Fe/Mg
ratio is less than $\phi$, then the expert system excludes the iron-rich shale specific lithology, and classifies the rock as having a magnesium-rich specific lithology.

In FIGS. 8A and 8B illustrate the ternary diagram and hybrid ternary diagrams, respectively, used to determine the range of compositions and specific lithologies for anhydrites, limestones, and dolomites classified according to the present methods. In FIG. 8A, ternary diagram 80 represents limestones 82 and anhydrites 84, based on the ratios between CaO, Fe$_2$O$_3$, and S. Rocks which plot in the region of area 82 can be considered to have a calcite specific lithology, and those within region 84 can be considered to have an anhydrite specific lithology.

Turning to FIG. 8B, similar to the previous discussions concerning the set of hybrid ternaries of FIG. 4, due to difficulties associated with attempting to discriminate specific lithologies using traditional ternary diagrams and the associated loss of resolution over the detailed chemistry of the rock resultant from normalization of values, a set of hybrid ternary diagrams 86 using normalized ratios are illustrated. In ternary plot A, the normalized ratio between MgO and Fe$_2$O$_3$ against the actual sulfur value is shown, and allows for the differentiation between anhydrite (+), calcite(•), dolomite (●), sand (#) and pyrite (●•) specific lithologies. Ternary plot B, in a similar fashion, illustrates the normalized ratio between MgO and CaO against the actual sulfur value (S), allowing for the differentiation between anhydritic calcites (+) and dolomites (●). In ternary plot C, the ratio of K$_2$O to silicon oxide (SiO$_2$) against the actual Fe$_2$O$_3$ value is illustrated, allowing for the expert system to distinguish between iron-rich calcite (●) and dolomites (●). Ternary plot D illustrates the normalized ratio of K$_2$O to silicon oxide (SiO$_2$) against the actual amount of magnesium (as the magnesium oxide, MgO). The information provided by this plot allows the expert system to distinguish between dolomites (●) versus anhydrites (+) and/or calcites (●). In ternary plot E, the normalized ratio between K$_2$O and Fe$_2$O$_3$ against the value of actual calcium (as the calcium oxide, CaO) in the system is illustrated. This plot allows for the differentiation of sand (#) and dolomite (●) from calcite (●). Finally, ternary plot F illustrates the normalized ratio between K$_2$O and MgO against the value of actual calcium (as the calcium oxide, CaO) in the system, allowing for the system to distinguish between sands (#), calcites (●), and dolomites (●). All of these ternary plots, A-F, can be utilized by the expert system, alone or in
combinations, in order to determine the specific lithology of anhydrites, dolomites, and evaporites.

FIG 9 illustrates a flow chart showing exemplary expert system logic for determining the specific lithology for carbonates and dolostones, based on the set of hybrid ternary diagrams in FIG. 8B. In the instance that the expert system has determined that the section of the rock formation under investigation has a carbonate general lithology classification, the expert system first evaluates the amount of potassium oxide (K) and iron oxide (Fe⁺) at decision prompt 90, where the additive value of K+Fe⁺ is based on the relative element oxides as determined by the ternary diagrams and hybrid ternary diagrams illustrated in FIG. 8A and 8B, respectively. If the calculated amount of (K + Fe⁺) is greater than κ (wherein κ ranges from about 1 to about 5), then the expert system determines that the rock is classified as having a shaley limestone specific lithology. If, however, the system computes the value of (K + Fe⁺) to be less than κ, then the system proceeds to decision prompt 92, wherein the percentage of sulfur relative to the amount of iron (S-Fe⁺ x 0.806) is computed and evaluated. If this value is determined to be greater than τ wt. % (wherein τ ranges from about 2 wt. % to about 7 wt. %), then the expert system excludes other specific lithology classifications and classifies the rock as having anhydritic-limestone specific lithology. Conversely, if at decision prompt 92 the value of S-(Fe⁺ x 0.806) is computed to be less than τ wt. %, then the expert system proceeds to decision prompt 94, wherein the calcium oxide-to-magnesium oxide ratio (Ca/Mg) is computed and evaluated. If the evaluation of the Ca/Mg ratio is less than μ (wherein μ ranges from about 15 to about 30), then the expert system determines that the rock has a dolostone specific lithology. If the Ca/Mg ratio is computed to be greater than μ, however, then the rock is considered to have a calcite specific lithology.

Continuing to refer to FIG. 9, in the instance that the expert system has determined that the rock formation has a general lithology classification of a dolostone, the expert system first evaluates the amount of potassium oxide (K) and iron oxide (Fe⁺) at decision prompt 96, where the additive value of (K+Fe⁺) is based on the relative element oxides as determined by the hybrid ternary diagrams illustrated in FIG. 8A and 8B. If the calculated amount of (K + Fe⁺) is greater than κ (wherein κ ranges from about 1 to about 5), then the expert system determines that the rock is classified as having a shaley dolomite specific lithology. If, however, the
system computes the value of \((K + Fe^+)\) to be less than \(k\), then the system proceeds to
decision prompt 98, wherein the magnesium oxide ternary value (MgT) is computed
and evaluated. If by computation and comparison MgT is determined to be less than
\(\beta_1\), then the rock is classified as having a dolomite specific lithology, excluding the
anhydritic- and calcic-dolomite classifications. However, in the event that the
magnesium oxide ternary value is greater than \(\beta_1\), the expert system proceeds to
decision prompt 100. The evaluation of the value of \(S-(Fe^+ x 0.806)\) based on relative
element oxide computations as determined from the ternary and/or hybrid ternary
diagrams of FIGS 8A and 8B determines if the dolostone has anhydritic- or calcic-
dolomite specific lithology. If the value of \(S-(Fe^+ x 0.806)\) at prompt 100 is greater
than \(\tau\) wt. % (wherein \(\tau\) ranges from about 2 wt. % to about 6 wt. %), then the expert
system excludes other specific lithology classifications and classifies the rock as
having anhydritic-dolostone specific lithology. If the value at decision prompt 100 is
calculated to be less than \(\tau\), then the rock is classified as having a calcic-dolomite
specific lithology.

FIG. 10 illustrates a flow chart showing exemplary expert system logic for
determining the specific lithology for evaporites, using an expert system as described
herein. When a section of a rock formation has been assigned a general lithology of
evaporite by the expert system and methods of the present invention, the specific
lithologies of the evaporite can be readily determined with little computational effort
by the expert system. At decision prompt 108, the expert system evaluates the
amount of chloride (Cl) present in the rock or rock formation, based upon the amount
of free chloride as reported by the logging tool. If the amount of chloride is
determined to be greater than \(\rho\) wt. % (wherein \(\rho\) ranges from about 8 wt. % to about
11 wt. %), the system then classifies the rock as having a salt (i.e., halite) specific
lithology. If, however, the rock cannot be classified as a salt or halite using this
determination, the system then proceeds to decision prompt 110. Based on the
evaluation of the magnesium oxide (MgO) chemistry of the rock formation, as
determined from one or more ternary diagrams or sets of hybrid ternary diagrams, the
expert system evaluates the amount of magnesium oxide (Mg) in the rock at decision
prompt 110. If the amount of magnesium oxide (Mg) at prompt 110 is computed to
be greater than \(\beta\) (wherein \(\beta\) ranges from about 1 wt. % to about 6 wt. %), then the
expert system classifies the rock as having a dolo-anhydrite specific lithology.
However, if the amount of Mg is computed to be less than \( \beta \), then the amount of calcium (based on the evaluation of the CaO chemistry of the rock formation) is evaluated at decision prompt 112, using a normalized or non-normalized calcium oxide-to-sulfur ratio (Ca/S). If the amount of calcium, based on the determinative value of the Ca/S ratio, is calculated to be greater than \( \alpha \) (wherein \( \alpha \) ranges from about 1.5 wt. % to about 6 wt. %, including about 2.1 wt. %), then the expert system assigns the rock a specific lithology of calcite-anhydrite, while if the amount of Ca, based on the calcium oxide-to-sulfur ratio, is calculated to be less than \( \alpha \), then the calcite-anhydrite classification is excluded, and the expert system assigns the rock an anhydride specific lithology.

FIG. 11 illustrates one type of several typical output forms that the lithology determination/estimation provided by the system of the present disclosure can provide. As shown therein, for a selected section of subterranean formation surrounding a well-bore that has been analyzed according to methods of the present invention, a graphical representation of the general lithology of a test well is shown at stratigraphic formation column 120. Similarly, the specific lithology of the same test well, providing greater detail as to the compositions of the various general lithologies at stratigraphic formation column 120, is illustrated in stratigraphic formation column 122. For example, to further illustrate the utility of the methods and systems of the present invention, between about 1100 feet and 1180 feet, the general lithology 120 as determined using the expert system and methods of the present invention suggests primarily a sandstone lithology, with a small band of shale near the 1100 foot mark. However, if the expert system and methods as described herein are utilized further, much more specific lithological detail is seen in section 122 for the same subterranean region of the wellbore. More specifically, it can be readily seen that the sandstone region between 1118 feet and about 1175 feet comprises primarily feldspathic sandstone, with intermittent bands of quartzose. Additionally, the small band of shale near the 1100 foot mark in specific lithology section 122 is shown to be not simply shale, but rather a mixture of iron-rich and magnesium-rich shale, with a lower band of sandy shale forming a boundary between the shale lithological region and the feldspathic sandstone lithological region.

MINERALOGY DETERMINATION

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The final step in the interpretation process, should such information be desired to be determined, is the determination of the mineralogy from the general and specific lithology information. The lithologic classification used in the methods of the present invention, and detailed in part above, allow the analyst to place constraints on the final petrophysical solution and customize the output accordingly. For example, in accordance with the methods of the present disclosure, in the instance of a feldspathic sand specific lithology, an analyst/user may want to only know or predict feldspars and, due to possible feldspar decomposition models, the presence of illite/smectite, chlorite, and/or kaolinite within the formation region. Using the methods of the present invention, such a determination is possible.

Minerals contained in a subterranean formation that can be determined and quantified in accordance with methods of the present invention include, but are not limited to, tectosilicates and non-ferromagnesian silicate minerals, including quartz (SiO₂), feldspars, including both plagioclase feldspars and K-feldspars (also known as K-spars, or alkali feldspars), such as microcline; phyllosilicates, including members of the chlorite group, such as chlorite [(Fe,Mg₃Al₄(Si₃Al₄O₁₀)(OH)₈]; and, the clays, including members of the illite/smectite group including but not limited to montmorillonite. In further aspects of the present invention, specific minerals that can be identified, and their amounts generally quantified, using the methods and systems of the present invention, include but are not limited to the following minerals, wherein the formulas are meant to be exemplary, but not inclusive: albite (NaAlSi₃O₈), anhydrite (CaSO₄), calcite (limestone, CaCO₃), coal (C), chlorite [(Mg,Fe₃⁺)₃(Si,Al)₄O₁₀(OH)₂•(Mg,Fe₂⁺)₂(OH)₆], dolomite (CaMg(CO₃)₂), glauconite [(K,Na)(Fe₃⁺,Al,Mg)₂(Si,Al)₄O₁₀(OH)₂], halite (NaCl), hematite (Fe₂O₃), illite/smectite [(K,Na,H)(Al,Fe,Mg)₃(Si,Al)₄O₁₀[(OH)₂•(H₂O)₆]], kaolinite [Al₂Si₂O₅(OH)₄], K-feldspar (KAlSi₃O₈), microcline (KAlSi₃O₈), orthoclase (KAlSi₃O₈), plagioclase, pyrite (FeS₂), quartz (SiO₂), and siderite (FeCO₃), as well as polymorphs and hydrates thereof.

Following the determination of the general and specific lithology of a subterranean formation surrounding a wellbore, the mineralogy of the formation can also be determined using the expert logic system and methods described herein. An exemplary logic algorithm for such mineralogy determination from the general and specific lithology information, using an Artificial Intelligence System (expert system) 20 as described herein, is illustrated in FIG. 12. In reference to this figure, as with all
of the flow diagrams and logic algorithms discussed herein, the numbers are exemplary only, and the coefficients listed in the formulas are averages of the best, general illustrative coefficients. However, it will be clear to those of skill in the art that these numbers and coefficients can be varied as appropriate, depending upon a number of factors, including the subterranean formation being logged and analyzed, and the specific output limitations desired by the user of the system.

As illustrated in FIG. 12, at process 150, an expert system 20 may first determine and define the K-feldspar (Ksp) Factor (referred to herein as “KspFac”), based on the determination of the general and specific lithology as previously described. The KspFac values determined for the various lithologies are then used by system 20 at appropriate decision prompts to aid in the process of determining the mineralogy. Following determination of the Ksp Factors at process 150, the system (20) may then proceed to process 152, to calculate the amount of illite based on the amount of observed K₂O, using the calculations illustrated. Following determination of the Ksp values and the illite determinative in process 152, the system proceeds to decision prompt 154. If the amount of observed potassium oxide (K₂O) is not greater than a predefined discriminator (e.g., about 3.0), and the ratio of potassium oxide-to-(K₂O + Fe₂O₃) is not less than a predefined discriminator (e.g., about 0.37), then there must necessarily be contributing amounts of illite, and the system proceeds to decision prompt 158. If, however, these requirements at prompt 152 are met, the system proceeds to process 156, wherein the Ksp value is assigned a value of 0, illite is determined to not be present and is similarly assigned a value of 0, and the amount of glauconite is calculated as shown. From process 156, the system proceeds to process 162 to process determination 162, and then proceeds to quantify the remaining minerals as appropriate or as specifically desired, based upon the observed elemental oxides and the stoichiometry of individual minerals, using determinative algorithms such as those illustrated in process 164.

If the requirements of decision prompt 154 are not met, the system proceeds to continue the preliminary mineralogical analysis. At decision prompt 158, the general lithology (GL) is evaluated; if the general lithology (GL) is sand or shale, then the system proceeds to decision prompt 160, wherein the amount of pyrite may be determined by the appropriate calculation using the amount of elemental sulfur (S) divided by an appropriate discriminator (e.g., about 0.535). If, however, at decision prompt 158, the general lithology (GL) has not been determined to be sand or shale,
then pyrite (Pyr) may be determined based on the amount of Fe₂O₃ (Fe) or elemental sulfur (S) at calculation process 162. Then, in a sequential fashion, as further illustrated in FIG. 12, the remaining minerals may be quantified as appropriate or as specifically desired, based upon the observed elemental oxides and the stoichiometry of individual minerals, using the determinative algorithms within process 164. The mineralogical composition data thus determined can be provided as output in the form of specific mineralogical information, or the information can be provided as mineralogical groups (i.e., clays). Exemplary outputs include stratigraphic columns illustrating mineralogy vs. depth for a specific portion of a subterranean formation surrounding an earth bore.

In accordance with further features of the present disclosure, the mineralogical information determined using an expert system such as described herein can be quantified using additional subterranean formation data available from a variety of sources. Suitable sources for providing such additional quantifying information include additional mineral data, such as that available from X-ray diffraction (XRD) analysis or thin section analysis of a core sample, user-specific constraints based upon the specific information being sought by the analyst regarding a specific subterranean formation, and conventional log data as described previously with regard to further quantifying the lithology determinations (e.g., NMR, GR, PE, Sonic, C/O, Caliper, and MRI-based porosity and permeability information).

The mineralogical data obtained in accordance with the methods of the present invention can be used to determine other petrologic and petrophysical information concerning a subterranean formation surrounding a wellbore. For example, the mineralogical content and amounts can be used to determine or predict such features as porosity, grain density, and permeability characteristics of the subterranean formation.

The following examples are included to demonstrate preferred embodiments of the invention. It should be appreciated by those of skill in the art that the techniques disclosed in the examples which follow represent techniques discovered by the inventors to function well in the practice of the invention, and thus can be considered to constitute preferred modes for its practice. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific embodiments which are disclosed and still obtain a like or similar result without departing from the scope of the invention.
EXAMPLES

Field examples illustrating exemplary methods of lithological and mineralogical analysis are described below, and in the associated and referenced figures. Core data used in the comparisons was obtained for all of the wells, and each of the wells was logged with the RockView™ logging sonde (Baker Atlas, Houston, TX), which utilizes the pulsed-neutron Formation Lithology Explorer (FLEX™) wireline logging tool (Baker Atlas, Houston, TX) to measure neutron capture and inelastic measurements. This logging sonde also utilizes the natural gamma ray Spectralog® II instruments (Baker Atlas, Houston, TX). The Spectralog® II and FLEX instruments measure formation concentrations for Ca, Si, Mg, S, C, Fe, Al, K, Ti, and Th based upon the principles of gamma ray spectroscopy. These tools were characterized based upon stationary measurements in formations located at the Instrument Characterization Center in Houston, Texas. Specifically, the measurement of Mg, Al, and C comes from an evaluation of the inelastic gamma ray energy spectrum, which is achieved through the use of an electronic, high frequency source of 14 MeV neutrons.

In FIGS. 13-15, the following abbreviations, and their associated meanings are used: “anhy” refers to the mineral anhydrite; “illi” refers to the mineral illite; “ilsm” refers to illite/smectite; “kaol” refers to the mineral kaolinite; “chlo” refers to the mineral chlorite; “glau” refers to the mineral glauconite; “hema” refers to the mineral hematite; “orth” refers to the mineral orthoclase; “pyri” refers to the mineral pyrite; “side” refers to the mineral siderite; “dolo” refers to the mineral dolomite; “calc” refers to the mineral calcite; “clay” refers generally to the clay minerals, including but not limited to any one or more of the clay minerals illite, kaolinite, chlorite, and montmorillonite; and, “quar” refers to the mineral quartz.

Example 1: Analysis of a Western Louisiana well.

To evaluate the quality and potential applications of the downhole lithology and mineralogy measurements to reservoir characterization, according to the methods of the present invention, geochemical well logs using the RockView™ wireline logging tool/sonde (Baker Atlas, Houston, TX) were obtained from a well in Western Louisiana. The results of the logs at a depth ranging from about 5050 feet to about 5400 feet below the surface, in comparison with core data analysis, are presented in the plots of FIG. 13.
As evidenced by the general lithology information presented in column A, the intervals in this well include carbonate, anhydrite, and some fairly clean sandstone at the lower depths. The large amounts of sulfur and calcium coupled with a lack of carbon provide clear indicators for the presence of anhydrite. As illustrated in column B, providing specific lithology information about the well, the carbonate is primarily limestone (sandy limestone) with some intermingled dolomite, while the anhydrite is primarily calcic anhydrite. As can be seen in the figure, results from core data analysis show good agreement with the log response for the general and specific lithologies, as well as for the mineralogies. For example, band 200 in stratigraphic column D illustrates that the rock formation at this depth has a mineralogy that is almost purely anhydrite, according to the core XRD data. This correlates well with stratigraphic column C, illustrating the mineralogy at this same depth as determined by the system of the present invention, which is similarly determined to be substantially anhydrite, with minor amounts of quartzite present. Exemplary bands 202, 204, and 206 similarly illustrate good correlations between the mineralogy as determined using the methods of the present invention compared to core XRD data at the same depth. Band 202, in both columns C and D, shows illite clay, siderite, K-feldspar, calcite and quartz present at a measured depth of about 5180 ft; band 204, in both columns C and D, shows the composition to be primarily carbonate at a measured depth of about 5290 ft, with minor amounts of illite and siderite; and, band 206, in both columns C and D, shows the composition at a measured depth of about 5370 ft to be primarily (>80%) quartz, with trace amounts of illite, K-feldspar, plagioclase, and carbonate.

Example 2: Analysis of a South American Well.

To further evaluate the quality and potential applications of the downhole lithology and mineralogy measurement methods disclosed herein to reservoir characterization, geochemical well logs using the Formation Lithology Explorer (FLEX™) wireline logging tool (Baker Atlas, Houston, TX) to quantify gamma-rays from neutron capture and inelastic scattering, were run in a test well in South America. These results are presented graphically in the schematic stratigraphic columns of the formation illustrated in FIG. 14. As illustrated therein in column A, showing the general lithology of the test section, the test well has a significant carbonate section at the top of the interval, followed by extremely clean sand zone
below, intermixed with several shale zones at the lower depths. As illustrated in column B, providing specific lithology information about the test well, the carbonate is a mixture of limestone (dolomitic and sandy limestone) and intermingled dolomite (including some sandy dolomite), while the sand zone is primarily quartz sand with intermingled bands of feldspathic sand, lithic sand, and quartzose. The specific lithology of column B also shows that the shale zones at the lower depths of the well are primarily iron-rich and sandy shales, as would be expected given the surrounding lithologies.

Comparison of the mineralogy vs. depth stratigraphic columns in FIG. 14 for the depth between a first measured depth (around XX50) and a second measured depth (about XX450), also illustrate an outstanding agreement between the mineralogy as determined by the systems and methods of the present invention, and core XRD data from the same well at the same depth interval. For example, the stratigraphic band 210 in column C of FIG. 14, representing the determined mineralogy for the test well, shows a mineralogy of primarily dolomite with minor amounts of illite and calcite. This is in very good agreement with the mineralogy as determined by XRD analysis of a core from the same well at this depth, as shown in column D, which shows the mineralogy to similarly be primarily dolomite with minor amounts of calcite. Exemplary bands 212, 214, and 216 similarly illustrate good correlations between the mineralogy as determined using the methods of the present invention compared to core XRD data at the same depth. Band 212, in both columns C and D, shows the rock to be primarily quartz, with minor amounts of illite and orthoclase; band 214, in both columns C and D, shows the composition to be about 50% quartz at this depth, with the remainder of the rock comprising illite, chlorite, K-feldspar, with notable amounts of (> 5%) pyrite; and, in band 216, both columns C and D show the composition at this depth to be about 50% quartz, with the remainder comprising primarily illite/smectite, and K-feldspar, with trace amounts of pyrite present as well.

Example 3: Analysis of a West Texas Well.

In yet another example to further evaluate the quality and potential applications of the downhole lithology and mineralogy measurement methods disclosed herein to reservoir characterization, geochemical well logs using the RockView™ logging sonde (Baker Atlas, Houston, TX) to measure gamma rays from
neutron capture and inelastic scattering, were run in a test well in the Permian Basin of West Texas, which has been previously detailed petrographically by a number of individuals [see, Saller, A.H., et al., AAPG Bulletin, v. 82(8): pp. 1528-1550 (1998), as well as references cited therein]. As illustrated in FIG. 15, the core mineralogy based on X-Ray Diffraction (XRD) displays an excellent agreement with the mineralogy as determined by the systems and methods of the present invention. As shown in column A of FIG. 15, providing general lithology information of the test well between a depth of about 4900 feet (measured depth, MD) and about 5250 feet (MD), the test well has a sand section at the top of the interval, followed by a significant and extremely clean carbonate zone below, and the lower depths below about 5100 feet (MD) being primarily sand zones intermixed with several carbonate zones. As illustrated in column B, providing specific lithology information about the test well, the sand zones are primarily feldspathic sands with interbedded bands of quartzose. The specific lithology of column B also shows that the carbonate zones of the well are primarily dolomitic with interbedded bands of limestone (both sandy and dolomitic limestone). Based on the lithological evaluation of this test well, very little clay is contained in this well.

Comparison of the mineralogy vs. depth stratigraphic columns for the depth between about 4900 feet (MD) and about 5250 feet (MD) also illustrates an outstanding agreement between the mineralogy as determined by the systems and methods of the present invention, and core mineralogy data from the same well at the same depth interval, as obtained using X-Ray Diffraction (XRD). For example, the stratigraphic band 220 in column C of FIG. 15, representing the determined mineralogy for the test well, shows a mineralogy of primarily dolomite with minor amounts of quartz and trace amounts of illite and calcite. This is in very good agreement with the mineralogy as determined by XRD (X-Ray Diffraction) analysis of a core from the same well at this depth, as shown in column D, which shows the mineralogy to similarly be primarily dolomite with minor amounts of quartz and trace amounts of illite. Exemplary bands 222, 224, and 226 similarly illustrate good correlations between the mineralogy as determined using the methods of the present invention displayed in column C compared to the core XRD data at the same depths presented in column D. Band 222, in both columns C and D, shows the rock to be a roughly equal mixture of dolomite and quartz, with remainder of the rock comprising minor amounts of orthoclase and plagioclase, and trace amounts of illite; band 224, in
both columns C and D, shows the composition to be significantly quartz at this depth, with the remainder of the rock comprising dolomite, anhydrite, K-feldspar, and plagioclase, as well as trace amounts of illite; and, in band 226, both columns C and D show the composition at this depth to be about 40% quartz, with the remainder comprising dolomite, K-feldspar, and plagioclase, with trace amounts of both illite, calcite, and anhydrite also present.

[0013] The invention has been described in the context of preferred and other embodiments and not every embodiment of the invention has been described. Obvious modifications and alterations to the described embodiments are available to those of ordinary skill in the art. The disclosed and undisclosed embodiments are not intended to limit or restrict the scope or applicability of the invention conceived of by the Applicants, but rather, in conformity with the patent laws, Applicants intends to protect all such modifications and improvements to the full extent that such falls within the scope or range of equivalent of the following claims.
What is claimed is:

1. A method for estimating the lithology and mineralogy of a formation surrounding a borehole, the method comprising:
   traversing the borehole with a well logging system on a logging tool string
   connected to surface equipment, the surface equipment including a computer and a
   processor coupled to one or more electromagnetic radiation systems or sources;
   obtaining wellbore data from the formation with the well logging system;
   sending the wellbore data to the processor;
   generating a lithology compositional model by a process that includes
   converting the wellbore data to elemental data as major element oxides and then
   generating ternary diagrams from the elemental data; and
   generating a complete quantitative mineralogy of the formation based on the
   lithology compositional model that has been generated;
   wherein the generation of the compositional model and the quantitative
   mineralogy is done by the processor using data that is obtained from the well logging
   system; and
   wherein the generation of the compositional model is performed by an artificial
   intelligence system.

2. The method of claim 1, wherein the well logging system comprises a neutron
   source.

3. The method of claim 2, wherein the neutron source is a pulsed neutron source.

4. The method of any one of claims 1 to 3, wherein the wellbore data obtained
   comprises elemental concentration per unit weight data.

5. The method of any one of claims 1 to 4, wherein the well logging system
   further comprises a gamma ray detector.

6. The method of claim 5, wherein the gamma ray detector is capable of
   measuring capture gamma radiation, inelastic gamma radiation, natural gamma radiation,
   and combinations thereof.
7. The method of any one of claims 1 to 6, wherein the artificial intelligence system is selected from the group consisting of look-up tables, cluster analysis systems, and combinations thereof.

8. The method of any one of claims 1 to 6, wherein the artificial intelligence system is selected from the group consisting of neural networks, genetic algorithm-based systems, fuzzy logic systems, and combinations thereof.

9. The method of any one of claims 1 to 8, wherein the generation of the lithology compositional model further comprises the generation of a general lithology compositional model.

10. The method of claim 9, wherein the general lithology compositional model comprises information on the individual chemical elements and combinations thereof in sands, shales, carbonates, evaporites, and coal, such that the elemental chemistry information only is used to determine the general lithology compositional model.

11. The method of any one of claims 1 to 10, wherein the generation of the lithology compositional model further comprises the generation of a specific lithology compositional model.

12. The method of claim 11, wherein the specific lithology compositional model comprises information on the individual chemical elements and combinations thereof of quartzose, feldspathic sand, lithic sand, shaley sand, limey quartzose, limey feldspathic sand, limey shaley sand, iron-rich shale, magnesium-rich shale, anhydrite, dolomitic anhydrite, calcic anhydrite, calcite, and/or dolomitic calcite, such that the elemental chemistry information is used to determine the specific lithology compositional model.

13. The method of any one of claims 1 to 12, wherein the quantitative mineralogy comprises information on the individual chemical elements and combinations thereof of minerals including quartz, K-feldspar, albite, calcite, dolomite, siderite, anhydrite, illite, smectite, chlorite, kaolinite, glauconite, pyrite, hematite, halite, and coal.

14. The method of any one of claims 1 to 13, further comprising obtaining additional wellbore data about the formation using secondary well logging data sources located on the logging tool string, wherein the additional wellbore data is collected at substantially the same time as the data used to generate the compositional model.
15. The method of claim 14, wherein the secondary well logging data collected at substantially the same time is obtained from sources comprising NMR logging data, bulk density data, resistivity data, sonic or acoustic data, neutron porosity data, photo-electric cross-section data, high definition induction log data, bulk density correction data, spectral gamma ray data, differential caliper data, core data, spontaneous potential logging data, and combinations thereof.

16. A method for estimating the lithology and mineralogy of a formation surrounding a borehole, the method comprising:
   traversing the borehole with a well logging system on a logging tool string connected to surface equipment, the system including a computer and a processor coupled to one or more electromagnetic radiation systems or sources;
   obtaining wellbore data from the formation with the well logging system on the tool string;
   sending the wellbore data to the processor;
   generating a general lithology compositional model by a process that includes converting the wellbore data to elemental data as major element oxides and then generating ternary diagrams from the elemental data; and
   generating a quantitative mineralogy of the formation;
   wherein the quantitative mineralogy is generated after the generation of the general lithology compositional model;
   wherein the generation of the compositional model and the quantitative mineralogy is done by the processor using data that is obtained from the well logging system; and
   wherein the generation of the compositional model is performed by an artificial intelligence system.

17. The method of claim 16, wherein the well logging system comprises a neutron source.

18. The method of claim 16 or 17, wherein the well logging system further comprises a gamma ray detector.

19. The method of claim 18, wherein the gamma ray detector is capable of measuring capture gamma radiation, inelastic gamma radiation, natural gamma radiation, and combinations thereof.
20. The method of any one of claims 16 to 19, wherein the artificial intelligence system is selected from the group consisting of expert systems, neural networks, genetic algorithm-based systems, fuzzy logic systems, look-up tables, cluster analysis systems, and combinations thereof.

21. The method of any one claims 16 to 20, wherein the general lithology compositional model comprises information on the individual chemical elements and combinations thereof of sands, shales, carbonates, evaporites, and coal, such that the elemental chemistry information only is used to determine the general lithology compositional model.

22. The method of any one of claims 16 to 21, further comprising the generation of a specific lithology compositional model.

23. The method of claim 22, wherein the specific lithology compositional model comprises information on the individual chemical elements and combinations thereof of quartzose, feldspathic sand, lithic sand, shaley sand, limey quartzose, limey feldspathic sand, limey shaley sand, iron-rich shale, magnesium-rich shale, anhydrite, dolomite anhydrite, calcic anhydrite, calcite, and/or dolomitic calcite, such that the elemental chemistry information is used to determine the specific lithology compositional model.

24. The method of any one of claims 16 to 23, wherein the quantitative mineralogy comprises information on the individual chemical elements and combinations thereof of minerals including quartz, K-feldspar, albite, calcite, dolomite, siderite, anhydrite, illite, smectite, chlorite, kaolinite, glauconite, pyrite, hematite, halite, and coal.

25. The method of any one of claims 16 to 21, further comprising obtaining additional wellbore data about the formation using secondary well logging data sources located on the logging tool string, wherein the additional wellbore data is collected at substantially the same time as the data used to generate the compositional model.

26. The method of claim 25, wherein the secondary well logging data collected is obtained from sources comprising NMR logging data, bulk density data, resistivity data, sonic or acoustic data, compensated neutron porosity data, photo-electric cross-section data, high definition induction log data, bulk density correction data, spectral gamma ray
data, differential caliper data, core data, spontaneous potential logging data, and combinations thereof.

27. An apparatus for making measurements of the lithology and mineralogy of an earth formation surrounding a borehole, the apparatus comprising:

(a) an electromagnetic radiation system which irradiates the earth formation surrounding at least a portion of the borehole and measures received radiation, the electromagnetic radiation system including at least one of:

(i) a neutron source and a neutron detector; and
(ii) a gamma-ray source and a gamma-ray detector; and

(b) a data processing system connected to the electromagnetic radiation system, the data processing system including a computer and a processor coupled to the electromagnetic radiation system;

wherein the processor comprises an artificial intelligence system that generates a lithology compositional model and a quantitative mineralogy of the formation based on the data received from the neutron detector or the gamma-ray detector;

wherein the lithology compositional model is generated before the quantitative mineralogy is generated, the lithology compositional model being generated by a process that includes converting the data received from the neutron detector or the gamma-ray detector to elemental data as major element oxides and then generating ternary diagrams from the elemental data using the artificial intelligence system; and

wherein the generation of the compositional model is performed by the artificial intelligence system within the processor.

28. The apparatus of claim 27, wherein the neutron source is a pulsed neutron source.

29. The apparatus of claim 27 or 28, wherein the gamma-ray detector is capable of measuring capture gamma radiation, inelastic gamma radiation, natural gamma radiation, or combinations thereof.

30. The apparatus of any one of claims 27 to 29, wherein the artificial intelligence system is selected from the group consisting of expert systems, neural networks, genetic algorithm-based systems, fuzzy logic systems, look-up tables, cluster analysis systems, or combinations thereof.
31. The apparatus of any one of claims 27 to 30, wherein the lithology compositional model comprises a general lithology compositional model, a specific lithology compositional model, or both a general lithology compositional model and a specific lithology compositional model.

32. A method for estimating the lithology and mineralogy of a formation surrounding a borehole, the method comprising:
   traversing the borehole with a well logging system on a logging tool string connected to surface equipment, the system including a computer and a processor coupled to one or more electromagnetic radiation systems or sources;
   obtaining wellbore data from the formation with the well logging system;
   sending the wellbore data to the processor;
   generating a general lithology compositional model;
   generating a specific lithology compositional model; and
   generating a quantitative mineralogy of the formation surrounding the borehole based on the general lithology, specific lithology, or both lithology compositional models that have been generated,
   wherein the quantitative mineralogy is generated after the generation of the specific lithology compositional model;
   wherein the generation of the compositional models is done by the processor using data that is obtained from the well logging system by a process that includes converting the wellbore data to elemental data as major element oxides and then generating ternary diagrams from the elemental data; and
   wherein the generation of the compositional models is performed by an artificial intelligence system.