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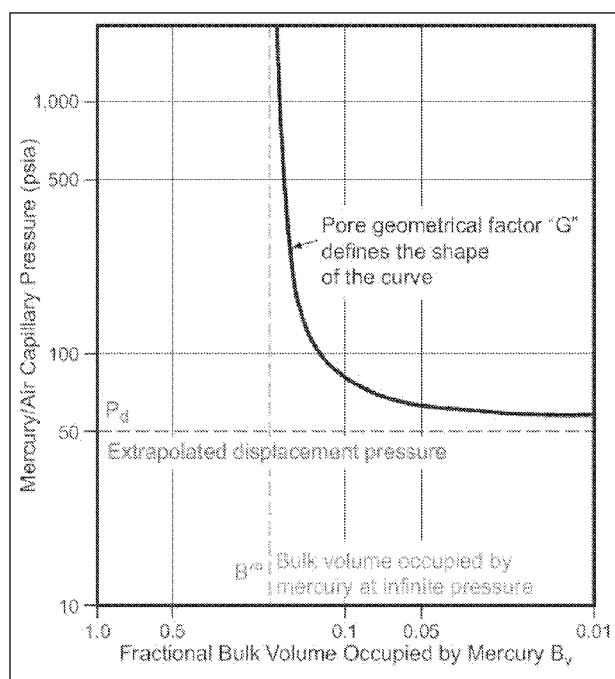
(54) Title: SYSTEMS, METHODS, AND COMPUTER-READABLE MEDIA FOR CONTINUOUS CAPILLARY PRESSURE
ESTIMATION

FIG. 1

(57) Abstract: Provided are methods, systems, and
computer-readable media for determining capillary
pressure in a basin/reservoir. Well log data is obtained
that includes permeability log data, porosity log data,
water saturation log data, and oil saturation log data.
Thomeer parameters for a multi-pore system of a
Thomeer model are determined by evaluating an ob-
jective function that measures the mismatch between
the well log data and modeled data having the
Thomeer parameters as input. The objective function
is iterative! evaluated using linear equality con-
straints, linear inequality constraints, and nonlinear
equality constraints until convergence criteria are met.



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PCT PATENT APPLICATION

**SYSTEMS, METHODS, AND COMPUTER-READABLE MEDIA FOR
CONTINUOUS CAPILLARY PRESSURE ESTIMATION**

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] This invention relates generally to sedimentary basin exploration and reservoir hydrocarbon production and, more particularly, to estimating capillary pressure for basin exploration and reservoir development and production.

2. Description of the Related Art

[0002] Various exploration and production systems are employed to find and extract oil, natural gas, and other resources from natural basins and reservoirs in the earth. Capillary pressure is a property used for basin exploration and reservoir development and production. For example, capillary pressure may be used to compute the original hydrocarbon in place (OHIP) and to estimate a recovery factor. Reservoir modeling and simulation enables characterization of static reservoir properties and prediction of reservoir dynamic behavior. Exploration and production activities and strategies are strongly impacted by reservoir modeling workflows and techniques. Accordingly, accurate capillary pressure estimation will contribute in reducing uncertainties on reservoir model predictions and in optimizing the exploration activities and the reservoir development plan. Capillary pressure may be used to determine the saturation distribution and the total in situ volumes of fluids (e.g., oil, water, and gas).

[0003] Capillary pressure data is obtained using special core analysis (SCAL). However, due to the expense and time associated with SCAL procedures, only a relatively few measurements of capillary pressure are typically performed. Additionally, the capillary pressure measurement support size used for SCAL is significantly smaller than the modeling support size used in reservoir simulation that uses the capillary pressure data. Capillary pressure is typically measured by mercury injection capillary pressure (MICP). Other

techniques for measuring capillary pressure may include core analysis using computer tomography (CT) and nuclear magnetic resonance (NMR).

SUMMARY OF THE INVENTION

[0004] Various embodiments of methods, computer-readable media, and systems for determining capillary pressure in a basin and a reservoir are provided herein. In some embodiments, a method is provided that includes accessing well log data from a well log for a well, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data and determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data. The Thomeer parameters include, for each pore system, a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure. Determining the Thomeer parameters includes determining a modeled permeability, determining a modeled porosity, and determining a modeled water saturation. Additionally, determining the Thomeer parameters includes evaluating an objective based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints. The

objective function includes
$$F(T) = \frac{w}{2} \|(1 - Sw_{FAL}) - So(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameter, Sw_{FAL} is the value of the water saturation data, and $So(T)$ is a modeled oil saturation for the current Thomeer parameter T . The one or more linear equality constraints include:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury, Pc is an applied capillary pressure, α is the conversion factor from mercury-air to oil-water, n is the number of pore systems in the reservoir, and ϕ_{FAL} is the porosity data. The one or more linear inequality constraints include:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

$$\text{If } Bv_i(Pc) \neq 0 \text{ then } Bv_i + 1(Pc) \leq Bv_i(Pc) \text{ for } 1 \leq i \leq n - 1,$$

$$Pd_i \leq Pd_i + 1 \text{ for } 1 \leq i \leq n-1,$$

and the one or more nonlinear equality constraints include:

$$K(T) = K_{FAL} \quad (20)$$

wherein $K(T)$ is the modeled permeability and K_{FAL} is the permeability from log data. The method further includes determining the capillary pressure of the basin/reservoir using a Thomeer model having the Thomeer parameters.

[0005] In other embodiments, a non-transitory tangible computer-readable storage medium having executable computer code stored thereon for determining capillary pressure in a basin reservoir is provided. The computer code includes a set of instructions that causes one or more processors to perform the following operations: accessing well log data from a well log for a well, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data and determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data. The Thomeer parameters include, for each pore system, a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure. Determining the Thomeer parameters includes determining a modeled permeability, determining a modeled porosity, and determining a modeled water saturation. Additionally, determining the Thomeer parameters includes evaluating an objective based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints. The

objective function includes
$$F(T) = \frac{w}{2} \|(1 - Sw_{FAL}) - So(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameter, Sw_{FAL} is the value of the water saturation data, and

$So(T)$ is a modeled oil saturation for the current Thomeer parameter T . The one or more linear equality constraints include:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury, Pc is an applied capillary pressure, α is the conversion factor from mercury-air to oil-water, n is the number of pore systems in the reservoir, and ϕ_{FAL} is the porosity data. The one or more linear inequality constraints include:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

$$\text{If } Bv_i(Pc) \neq 0 \text{ then } Bv_{i+1}(Pc) \leq Bv_i(Pc) \text{ for } 1 \leq i \leq n-1,$$

$$Pd_i \leq Pd_{i+1} \text{ for } 1 \leq i \leq n-1,$$

and the one or more nonlinear equality constraints include:

$$K(T) = K_{FAL}(20)$$

wherein $K(T)$ is the modeled permeability and K_{FAL} is the permeability log data. The computer code includes a set of instructions that causes one or more processors to perform the following operations: determining the capillary pressure of the reservoir using a Thomeer model having the Thomeer parameters.

[0006] Additionally, in some embodiments, a system is provided that includes well log data, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data, one or more processors, and a tangible non-transitory computer-readable memory having executable computer code stored thereon for determining capillary pressure in a basin and a reservoir. The computer code includes a set of instructions that causes one or more processors to perform the following operations: accessing well log data from a well log for a well, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data and determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data. The Thomeer parameters include, for each pore system, a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure. Determining the Thomeer parameters includes determining a modeled permeability, determining a modeled porosity, and determining a modeled water saturation for the current Thomeer parameter T . Additionally, determining the Thomeer parameters includes evaluating an objective based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints. The objective function includes

$$F(T) = \frac{w}{2} \|(1 - Sw_{FAL}) - So(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameter, Sw_{FAL} is the value of the water saturation data, and $So(T)$ is a modeled oil saturation. The one or more linear equality constraints

include:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury, Pc is an applied capillary pressure, α is the conversion factor from mercury-air to oil-water, n is the number of pore systems in the reservoir, and ϕ_{FAL} is the porosity data. The one or more linear inequality constraints include:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

$$\text{If } Bv_i(Pc) \neq 0 \text{ then } Bv_{i+1}(Pc) \leq Bv_i(Pc) \text{ for } 1 \leq i \leq n-1,$$

$$Pd_i \leq Pd_{i+1} \text{ for } 1 \leq i \leq n-1,$$

and the one or more nonlinear equality constraints include:

$$K(T) = K_{FAL}$$

wherein $K(T)$ is the modeled permeability and K_{FAL} is the permeability from log data. The computer code further includes a set of instructions that causes one or more processors to perform the following operations: determining the capillary pressure of the basin/reservoir using a Thomeer model having the Thomeer parameters.

[0007] Further, in some embodiments, a computer-implemented method for determining capillary pressure is provided. The method includes accessing well log data from a well log for a well, the well log data including permeability log data, porosity log data, water saturation log data, and oil saturation log data. The method further includes evaluating an objective function measuring the different between the permeability log data and a modeled permeability, the porosity log data and a modeled porosity, and the oil saturation log data and a modeled oil saturation, the modeled permeability, the modeled porosity, and the modeled oil saturation each a function of Thomeer parameters. Additionally, the method includes determining the capillary pressures of the basin and a reservoir using a Thomeer model having the Thomeer parameters, the Thomeer parameters comprising a fractional bulk volume, for each pore system, a pore geometrical factor, and a minimum entry pressure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 is a graph of a Thomeer function representing an MICP B_v -curve for a mono-modal pore system according to the prior art;

[0009] FIG. 2 is a block diagram of a process for estimating Thomeer parameters from standard well log data and determining capillary pressure in accordance with an embodiment of the present invention;

[0010] FIG. 3 is a block diagram of an optimization process for the objective function and constraints for estimating Thomeer parameters in accordance with an embodiment of the present invention;

[0011] FIG. 4 is a block diagram of a system for estimating Thomeer parameters from standard well log data and determining capillary pressure in accordance with an embodiment of the present invention;

[0012] FIG. 5 is a block diagram of a computer in accordance with an embodiment of the present invention;

[0013] FIGS. 6-10 are graphs depicting the results of validation testing of the estimation of Thomeer parameters in accordance with an embodiment of the present invention;

[0014] FIGS. 11-15 are plots of modeled data and actual data for the five synthetic wells used for the validation testing of the estimation of Thomeer parameters in accordance with an embodiment of the present invention.

[0015] While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but to the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION OF T

[0016] As discussed in more detail below, provided in some embodiments are systems, methods, and computer-readable media for determining capillary pressure in a basin and a reservoir. Well log data is obtained from a well log for a well and used to determine Thomeer parameters for each pore system, i.e., minimum entry pressure, pore geometrical factor, and fractional bulk volume occupied, used in a Thomeer model for determining capillary pressure. The well log data may include permeability log data, porosity log data, water saturation log data, and oil saturation log data. The Thomeer parameters are determined by evaluating an objective function that measures the mismatch between the well log data and modeled data having the Thomeer parameters as input. The objective function is iteratively evaluated using linear equality constraints, linear inequality constraints, and nonlinear equality constraints until convergence criteria are met. In some embodiments, the evaluation may be performed using sequential quadratic programming. The determined capillary pressures for a basin and a reservoir may be provided for basin exploration, prospect evaluation, and reservoir modeling and reservoir simulation.

[0017] As will be appreciated, mercury injection capillary pressure (MICP) may be used with core samples to determine capillary pressures and pore size distributions. The mercury-air systems used with MICP may be converted to oil-water systems that typically exist in basin and a reservoir. The Thomeer model is based on an observed hyperbolic relationship between the amount of mercury entering a pore system in an MICP experiment and the applied mercury pressures. The Thomeer model provides an empirical formula for the occupied fractional bulk volume B_v and the mercury pressures P_c , as shown in Equation 1 as follows:

$$[0018] \quad B_v(P_c) \approx \begin{cases} B_{v,\infty} \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) & \text{for } P_c > P_d \\ 0 & \text{elsewhere} \end{cases} \quad (1)$$

[0019] Where $B_v(P_c)$ is the fractional bulk volume occupied by mercury at capillary pressure P_c , $B_{v,\infty}$ is the fractional bulk volume occupied by mercury at infinitely high capillary pressure, G is the pore geometrical factor, P_c is the applied capillary pressure, and P_d is the minimum entry pressure.

[0020] Thus, the shape of the function described above in Equation 1 is determined by the three Thomeer parameters described above: P_d , G , and $B_{v,\infty}$. The Thomeer parameterization

for MICP experiments may be used to describe the internal architecture of a basin and a reservoir pore system. FIG. 1 depicts a Thomeer function representing an MICP B_v -curve for a mono-modal pore system.

[0021] As shown in the figure, the asymptotes for the Thomeer parameters B_v and P_d are indicated. The pore geometrical factor G determines the curvature of the illustrated MICP B_v -curve, such that a large value of G results in a gradual onset and small value of G results in a sudden and sharp onset. For multi-modal systems (e.g., carbonates), a summation of up to three different Thomeer hyperbolas may be used to constitute a complete MICP B_v -curve. Because each such hyperbola would upscale independently, multi-modality is left out of the upscale derivation. Thus, unless otherwise noted, pore systems employed in the techniques described below may be assumed to be mono-modal. However, the techniques described below are not restricted to mono-modal pore systems and may be used with multi-modal pore systems.

[0022] Additionally, in some embodiments $B_{v,\infty}$ may be assumed to equal ϕ . Thus, applying this assumption to Equation 1, in such embodiments the Thomeer formula is shown in Equation 2 as follows:

$$[0023] \quad B_v(P_c) \approx \begin{cases} \phi \cdot \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) & \text{for } P_c > P_d \\ 0 & \text{elsewhere} \end{cases} \quad (2)$$

[0024] Where $B_v(P_c)$ is the fractional bulk volume occupied by mercury at capillary pressure P_c , ϕ is the porosity, G is the pore geometrical factor, P_c is the applied capillary pressure, and P_d is the minimum entry pressure.

[0025] Accordingly, Equation 2 may be expressed in terms of porosity and mercury saturations, as shown below in Equations 3 and 4 as follows:

$$[0026] \quad B_v(P_c) \approx \phi S_{Hg}(P_c) \quad (3)$$

[0027] Where $B_v(P_c)$ is the fractional bulk volume occupied by mercury at capillary pressure P_c , ϕ is the porosity, $S_{Hg}(P_c)$ is the mercury saturation at capillary pressure P_c , and P_c is the applied capillary pressure.

$$[0028] \quad S_{Hg}(P_c) \approx \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) \quad (4)$$

[0029] Wherein $S_{Hg}(P_c)$ is the mercury saturation at capillary pressure P_c , P_c is the applied capillary pressure, G is the pore geometrical factor, and P_d is the minimum entry pressure.

[0030] As will be appreciated, the conversion from mercury saturation to actual reservoir fluid saturation (i.e., S_{HG} to S_{oil}) may be performed using the interfacial tension values for oil-brine-rock and for Hg-air-rock (or Hg-vapor-rock).

[0031] Typically estimations using Thomeer analysis involve the fitting of the Thomeer hyperbola to core plug MICP data by determining the Thomeer parameters from such data. This results in the full characterization of the entire pore space of each core plug. However, such core plug MICP data is very sparse and Thomeer parameters estimation from MICP data will generate capillary pressure data with a high degree of uncertainty. For example, a core plug may have a typical volume of about 10 cm³ and reservoir element, as probed by wire-line logs such as resistivity, may represent a reservoir volume equivalent billions of core plugs, while a typical reservoir model grid cell is about 250m x 250m x 1m. Consequently, reservoir modeling and simulation (e.g., for reserve estimation and production forecast) based on such capillary pressure data may also be highly uncertain.

[0032] FIG. 2 depicts a process 200 for estimating the Thomeer parameters from standard well logs, such as those obtained from fluid analysis logs. Some or all steps of the process 200 may be implemented as executable computer code stored on a non-transitory tangible computer-readable storage medium and executed by one or more processors of a special-purpose machine, e.g., a computer programmed to execute the code. Initially, well log data is obtained (block 202). The obtained well log data 204 may include porosity data, water saturation data, oil saturation data, and permeability data. Next, as described in detail below, the Thomeer parameters for the Thomeer model are estimated from the well log data (block 206) by minimizing an objective function measuring a mismatch between observed data and predicted data from a theoretical model having the Thomeer parameters as an input. Next, the estimated Thomeer parameters are inputted into the Thomeer formula (block 208). Based on these parameters, capillary pressure is estimated for a reservoir using the Thomeer equation (block 210). The estimated capillary pressures may then be used in further basin exploration, prospect evaluation, and reservoir modeling and simulations (block 212).

[0033] As mentioned above, embodiments of the present invention may estimate Thomeer parameters from "standard" well logs having, for example, porosity data, water saturation

data, oil saturation data, and permeability data. As described in detail below, the estimation of Thomeer parameters from well log data is based on an inverse problem theory. Accordingly, the Thomeer parameters are estimated by minimizing an objective function measuring a mismatch between observed data and predicted data from a theoretical model having the Thomeer parameters as an input. In the techniques described below, the Thomeer parameters may be abbreviated using Equation 5 as follows:

$$[0034] \quad T = (Bv_i(Pc), G_i, Pd_i)_{1 \leq i \leq n} \quad (5)$$

[0035] wherein T is the abbreviation for the Thomeer parameters, n is the number of pore systems in the reservoir, $Bv_i(Pc)_{1 \leq i \leq n}$ is the fractional bulk volume occupied by mercury at infinitely high capillary pressure, Pc is the applied capillary pressure, $(G_i)_{1 \leq i \leq n}$ is the pore geometrical factor and $(Pd_i)_{1 \leq i \leq n}$ is the minimum entry pressure.

[0036] As explained above, the well log data may include a porosity log, water saturation log, oil saturation log, and permeability log. A porosity model using the multi-pore system porosity definition may be represented by Equation 6 as follows:

$$[0037] \quad \phi(T) = \alpha \sum_{i=1}^n Bv_i \quad (6)$$

[0038] Where ϕ is the porosity, α is the conversion factor from mercury-air to oil-water, n is the number of pore systems in the reservoir, and Bv_i is the fractional bulk volume occupied by mercury.

[0039] An oil saturation model using the Thomeer equations may be represented by Equations 7 and 8 as follows:

$$[0040] \quad So_i(G_i, Pd_i) = Bv_i^\infty * \exp\left(\frac{-G_i}{\log(Pc) - \log(Pd_i)}\right) \quad (7)$$

[0041] Where $So_i(G_i, Pd_i)$ is the modeled oil saturation using Thomeer equations for the pore system i described by the Thomeer parameters $(Bv_i(Pc), G_i, Pd_i)$, Bv_i^∞ is the fractional bulk volume occupied by mercury at infinitely high capillary pressure, Pc is the applied capillary pressure, G_i is the pore geometrical factor and Pd_i is the minimum entry pressure.

$$[0042] \quad So(T) = \frac{1}{\phi} \sum_{i=1}^n Bv_i * So_i(G_i, Pd_i) \quad (8)$$

[0043] Where $So(T)$ is the modeled oil saturation using Thomeer equations for the multi-modal pore system described by the Thomeer parameters T at capillary pressure P_c , ϕ is the porosity, $So_i (G_i, Pd_i)$ is the modeled oil saturation using Thomeer equations for the pore system i described by the Thomeer parameters $(Bv_i(P_c), G_i, Pd_i)$, Bv_i is the fractional bulk volume occupied by mercury, G_i the pore geometrical factor and Pd_i is the minimum entry pressure.

[0044] An absolute permeability model may be represented using the Buitting-Clerke equation, as shown below in Equation 9:

$$[0045] \quad K(T) = 506 * \sum_{i=1}^n \frac{Bv_i(P_c)}{Pd_i^2} \exp(-4.43\sqrt{G_i}) \quad (9)$$

[0046] Wherein $K(T)$ is the modeled permeability using the using Thomeer equations for the multi-modal pore system described by the Thomeer parameters T at capillary pressure P_c , $Bv_i(P_c)$ is the fractional bulk volume occupied by mercury at infinitely high capillary pressure, P_c is the applied capillary pressure, G_i is the pore geometrical factor and Pd_i is the minimum entry pressure.

[0047] As mentioned above, the Thomeer parameters are estimated from well log data based on an inverse problem theory. The inverse problem formulation includes an objection function minimized using linear and nonlinear constraints. The objection function is shown in Equation 10 as follows:

$$[0048] \quad F(T) = \frac{w}{2} \|(1 - Sw_{FAL}) - So(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2 \quad (10)$$

[0049] Wherein $F(T)$ is the objective function using Thomeer equations for the multi-modal pore system described by the Thomeer parameters T , w is the, Sw_{FAL} is the water saturation log value (e.g., from a fluid analysis log), $So(T)$ is the modeled oil saturation using Thomeer equations for the multi-modal pore system described by the Thomeer parameters T at capillary pressure P_c , and T is the abbreviation for the Thomeer parameters.

[0050] The linear equality constraints are shown by Equation 11 as follows:

$$[0051] \quad \sum_{i=1}^n Bv_i(P_c) = \alpha * \phi_{FAL} \quad (11)$$

[0052] Wherein $Bv_i(P_c)$ is the fractional bulk volume occupied by mercury at capillary pressure P_c , P_c is the applied capillary pressure, α is the conversion factor from mercury-air

to oil-water, n is the number of pore systems in the reservoir, and ϕ_{FAL} is the porosity log data (e.g., from a fluid analysis log).

[0053] The linear inequality constraints are shown by Equations 12-16 as follows:

$$[0054] \quad Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n \quad (12)$$

[0055] Wherein Bv_i is the fractional bulk volume occupied by mercury, $Bv_i(Pc)$ is the fractional bulk volume occupied by mercury at capillary pressure Pc , Pc is the applied capillary pressure, and n is the number of pore systems in the reservoir.

$$[0056] \quad G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n \quad (13)$$

[0057] Wherein G_i is the pore geometrical factor and n is the number of pore systems in the basin/reservoir.

$$[0058] \quad Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n \quad (14)$$

[0059] Wherein Pd_i is the minimum entry pressure and n is the number of pore systems in the reservoir.

$$[0060] \quad \text{if } Bv_i(Pc) \neq 0 \text{ then } Bv_{i+1}(Pc) \leq Bv_i(Pc) \text{ for } 1 \leq i \leq n-1 \quad (15)$$

[0061] Wherein Bv_i is the fractional bulk volume occupied by mercury, $Bv_i(Pc)$ is the fractional bulk volume occupied by mercury at capillary pressure Pc , Pc is the applied capillary pressure, and n is the number of pore systems in the reservoir.

$$[0062] \quad Pd_i \leq Pd_{i+1} \text{ for } 1 \leq i \leq n-1 \quad (16)$$

[0063] Wherein Pd_i is the minimum entry pressure and n is the number of pore systems in the reservoir.

[0064] The nonlinear equality constraints are shown by Equation 17 as follows:

$$[0065] \quad K(T) = K_{FAL} \quad (17)$$

[0066] Wherein $K(T)$ is the modeled permeability using the using Thomeer equations for the multi-modal pore system described by the Thomeer parameters T and K_{FAL} is the permeability log data (e.g., from a fluid analysis log).

[0067] In some embodiments, the objective function is evaluated using sequential quadratic programming (SQP). By way of background, SQP may be used to solve

differentiable nonlinear programming problems having forms shown by Equations 18-22 as follows:

$$[0068] \quad \min f(x) \quad (18)$$

$$[0069] \quad x \in \mathbb{R}^n \quad (19)$$

$$[0070] \quad x_l \leq x \leq x_u \quad (20)$$

$$[0071] \quad g_j(x) = 0, j = 1, \dots, m_e \quad (21)$$

$$[0072] \quad g_j(x) \geq 0, j = m_e + 1, \dots, m \quad (22)$$

[0073] Wherein x is an n -dimensional parameter vector and all problems functions $f(x)$ and $g_j(x), j=1, \dots, m$ are assumed to be continuously differentiable. As will be appreciated, SQP is the standard general purpose technique to solve smooth nonlinear optimization problems under the following assumptions: the problem is not large, functions and gradients can be evaluated with sufficiently high precision, and the problem is smooth and well-scaled. Accordingly, in such embodiments a quadratic programming sub-problem may at solved at any iteration by linearizing the constraints and quadratically approximating the Lagrangian function shown in Equation 23 as follows:

$$[0074] \quad L(x, u) = f(x) - \sum_{j=1}^m u_j g_j(x) \quad (23)$$

[0075] Wherein x is the primal variable and $u = (u_1, \dots, u_m)^T$ is the Lagrange multiplier vector.

[0076] FIG. 3 depicts the optimization process 300 for the objective function and constraints described above. Some or all steps of the process 300 may be implemented as executable computer code stored on a non-transitory tangible computer-readable storage medium and executed by one or more processors of a special-purpose machine, e.g., a computer programmed to execute the code. The process 300 begins at initialization block 302 and is an iterative process that is stopped after convergence criteria are met. The initialization may include obtaining the well log data and receiving any other data or parameters used in the subsequent determinations. As shown in FIG. 3, Equation 5, the abbreviation for the Thomeer parameters, is depicted in block 304 and represents the Thomeer parameters to be estimated via the process 300. Next, the various equations for the well log data as a function of the Thomeer parameters are determined. As shown in FIG. 3, Equation 7 for estimating the

oil saturation is depicted in block 306. Subsequently, the modeled oil saturation as a function of the Thomeer parameters is estimated, as shown by Equation 8 depicted in block 308. Additionally, as mentioned above, the modeled porosity as a function of the Thomeer parameters is estimated, as shown by Equation 6 depicted in block 310. Similarly, the modeled permeability as a function of the Thomeer parameters is estimated, as shown by Equation 9 depicted in block 312.

[0077] The evaluation of the equations described above is performed by minimizing the objective function described above in Equation 10 using the linear equality constraints described above in Equation 11, the linear inequality constraints described above in Equations 12-16, and the nonlinear inequality constraints described above in Equation 17 (block 314). As mentioned above, in some embodiments the objection function may be optimized using SQP techniques. Next convergence criteria are evaluated to determine if the criteria are met (decision block 316). If the convergence criteria are not met (line 318), the next iteration of the process 300 is executed (block 320). In this manner, the equations described above are evaluated until the convergence criteria of the minimization of the objective function are met. If the convergence criteria are met (line 322), the process may stop (block 324) and the values for the Thomeer parameters may be used in subsequent calculations of capillary pressure.

[0078] FIG. 4 depicts a system 400 for determining capillary pressure in accordance with an embodiment of the present invention. The system 400 may include well log data 402 and server 404 having a Thomeer parameter estimation process 406 and a capillary pressure estimation process 408. Additionally, FIG. 4 also illustrates a network 410 and a reservoir modeling and simulation system 412. As will be appreciated, well log data 402 may be obtained from "standard" well logging techniques, such as a fluid analysis log, Facimage, and other techniques. Advantageously, no additional procedures, such as core plugs, are required to obtain data for estimating the Thomeer parameters and the capillary pressure. As noted above, in some embodiments the well log data includes porosity data 414, saturation data 416 (e.g., water saturation data and oil saturation data), and permeability data 418.

[0079] As described above, the server 404 may execute a Thomeer parameter estimation process 406 to estimate Thomeer parameters 420 from the well log data 402, according to the equations and processes described above. As described above, the Thomeer parameters 420 are estimated from the well log data 402 by minimizing an objective function measuring the mismatch between the observed well log data 402 and the predicted data from a theoretical

model having the Thomeer parameters as the input. The server 404 may also execute the capillary pressure estimation process 408 to estimate capillary pressures 422 from the estimated Thomeer parameters 420 using the Thomeer equations described above. The estimated capillary pressures 422 may be provided to the reservoir modeling and simulation system 412, such as via the network 410. The reservoir modeling and simulation system may produce a reservoir model 424 and a reservoir simulation 426 using the capillary pressure as an input, in addition to other inputs typically provided for such models and simulations.

[0080] Advantageously, the determination of capillary pressure according to the techniques described above is relatively quick as they are based on numerical modeling and not laboratory experiences. Additionally, the cost of estimating capillary pressure may be reduced by using standard well log data for the estimation of capillary pressure as described above instead of laboratory experiments. Moreover, the capillary pressure for the entire well is estimated and is not limited to only the relatively small number of core samples having SCAL. Accordingly, the estimated capillary pressure reflects the capillary pressures in the well and not just for the small plug volume used for SCAL. Consequently, the capillary pressure is more appropriate for reservoir simulation and modeling wherein the modeling cell size may be closer to the well neighborhood scale than to the core scale.

[0081] FIG. 5 depicts a computer 500, such as a server, in accordance with an embodiment of the present invention. The computer depicted in FIG. 5, and other computers providing comparable capabilities, may be used in conjunction with the present techniques. The computer 500 may communicate over a network 502, described further below. The computer 500 may include various internal and external components that contribute to the function of the device and which may allow the computer 500 to function in accordance with the techniques discussed herein. As will be appreciated, various components of computer 500 may be provided as internal or integral components of the computer 500 or may be provided as external or connectable components. It should further be noted that FIG. 5 depicts merely one example of a particular implementation and is intended to illustrate the types of components and functionalities that may be present in computer 500.

[0082] In various embodiments, the computer 500 may be a server, a desktop computer, a laptop computer, a tablet computer, a smartphone, or other types of computers. As shown in FIG. 5, the computer 500 may include one or more processors 504 and memory 506. Additionally, the computer 500 may include, for example, an interface 508, a display 510, an input device 512, input/output ports 514 and a network interface 516.

[0083] The display 510 may include a cathode ray tube (CRT) display, a liquid crystal display (LCD), an organic light emitting diode (OLED) display, or other types of displays. The display 510 may display a user interface (e.g., a graphical user interface) and may display various function and system indicators to provide feedback to a user, such as power status, call status, memory status, etc. In some embodiments, the display 510 may include a touch-sensitive display (referred to as a “touch screen”). In such embodiments, the touch screen may enable interaction with the computer via a user interface displayed on the display 510. In some embodiments, the display 510 may display a user interface for implementing the techniques described above, such as, for example, selecting well log data, initiating determination of Thomeer parameters, viewing the status of the processes described above, viewing the determined Thomeer parameters, viewing the determined capillary pressures, and so on.

[0084] The one or more processors 504 may provide the processing capability required to execute the operating system, programs, user interface, and functions of the computer 500. The one or more processors 500 may include microprocessors, such as “general-purpose” microprocessors, a combination of general and special purpose microprocessors, and Application-Specific Integrated Circuits (ASICs). The computer 500 may thus be a single processor system or a multiple processor system. The one or more processors 500 may include single-core processors and multicore processors and may include graphics processors, video processors, and/or related chip sets.

[0085] The memory 506 may be accessible by the processor 502 and other components of the computer 500. The memory 506 (which may include tangible non-transitory computer readable storage mediums) may include volatile memory and non-volatile memory accessible by the processor 502 and other components of the computer 500. The memory 506 may store a variety of information and may be used for a variety of purposes. For example, the memory 506 may store the firmware for the computer 500, an operating system for the computer 500, and any other programs or executable code necessary for the computer 500 to function. The memory 506 may include volatile memory, such as random access memory (RAM) and may also include non-volatile memory, such as ROM, a solid state drive (SSD), a hard drive, any other suitable optical, magnetic, or solid-state storage medium, or a combination thereof.

[0086] The memory may store executable computer code that includes program instructions 518 executable by the one or more processors 502 to implement one or more embodiments of the present invention. For example, the processes 100, 200, and 300

described above may be implemented in program instructions 518. Thus, in some embodiments program instructions 518 may include instructions 520 for Thomeer parameter estimation (e.g., the Thomeer parameter estimation process 406) and instructions 522 for capillary pressure estimation (e.g., the capillary pressure estimation process 408). The program instructions 518 may include a computer program (which in certain forms is known as a program, software, software application, script, or code). A computer program may be written in a programming language, including compiled or interpreted languages, or declarative or procedural languages. A computer program may include a unit suitable for use in a computing environment, including as a stand-alone program, a module, a component, a subroutine, etc., that may or may not correspond to a file in a file system. The program instructions 518 may be deployed to be executed on computers located locally at one site or distributed across multiple remote sites and interconnected by a communication network (e.g., network 502).

[0087] The interface 508 may include multiple interfaces and may couple various components of the computer 500 to the processor 502 and memory 504. In some embodiments, the interface 508, the processor 502, memory 504, and one or more other components of the computer 500 may be implemented on a single chip. In other embodiments, these components and/or their functionalities may be implemented on separate chips.

[0088] The computer 500 also includes a user input device 512 that may be used to interact with and control the computer 500. In general, embodiments of the computer 500 may include any number of user input devices 512, such as a keyboard, a mouse, a trackball, a digital stylus or pen, buttons, switches, or any other suitable input device. The input device 512 may be operable with a user interface displayed on the computer 500 to control functions of the computer 500 or of other devices connected to or used by the computer 500. For example, the input device 500 may allow a user to navigate a user interface, input data to the computer 500, select data provided by the computer 500, and direct the output of data from the computer 500.

[0089] The computer 500 may also include an input and output port 514 to enable connection of devices to the computer 500. The input and output 514 may include an audio port, universal serial bus (USB) ports, AC and DC power connectors, serial data ports, and so on. Further, the computer 500 may use the input and output ports to connect to and send or receive data with other devices, such as other computers, printers, and so on.

[0090] The computer 500 depicted in FIG. 5 also includes a network interface 516, such as a network interface card (NIC), wireless (e.g., radio frequency) receivers, etc. For example, the network interface 516 may include known circuitry for communicating with communication networks via electromagnetic signals transmitted over a wired or wireless connection. Such circuitry may include, for example, antennas, amplifiers, transceivers, receivers, processors, and so on. The network interface 516 may communicate with various communication networks (e.g., network 502), such as the Internet, an intranet, a cellular telephone network, a wireless local area network (LAN), a metropolitan area network (MAN), or other suitable communication networks. The network interface 516 may implement any suitable communications standard, protocol and/or technology, including wired Ethernet, wireless Ethernet (Wi-Fi) (e.g., IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and/or IEEE 802.11n), a 3G network (e.g., based upon the IMT-2000 standard), high-speed downlink packet access (HSDPA), wideband code division multiple access (W-CDMA), code division multiple access (CDMA), time division multiple access (TDMA), a 4G network (e.g., IMT Advanced, Long-Term Evolution Advanced (LTE Advanced), etc.), and any other suitable communications standard, protocol, or technology.

[0091] FIGS. 6-10 depict the results of various validation tests to estimate reservoir capillary pressure in accordance with the techniques described herein. The validation testing is based on reference sets of Thomeer parameters that are used to populate five synthetic wells. For each synthetic well, porosity, permeability, and saturation logs are generated using the models described above in Equations 6-10. For validation, the actual Thomeer parameters are assumed to be unknown and the synthetic porosity, permeability, and saturation log data is used to estimate Thomeer parameters and, thus, the capillary pressure.

[0092] FIG. 6 depicts graphs of the model well data vs. the estimated well data and illustrates the efficiency of the optimization of the objective function using the linear equality constraints, linear inequality constraints, and nonlinear equality constraints. FIG. 6 depicts a first graph 600 illustrating estimated saturation data vs. modeled saturation data, a second graph 602 illustrating estimated permeability data vs. modeled permeability data, and a third graph 604 illustrating estimated porosity data vs. modeled porosity data. The process took less than one minute to reach the convergence criteria and determine a solution that matches the saturation data and honors the linear constraints on the porosity and the non-linear constraints on the permeability.

[0093] FIG. 7 depicts graphs of the estimated Thomeer parameters (G , Bv , and Pd) vs. the actual Thomeer parameters for a macro system. FIG. 7 depicts a first graph 700 illustrating estimated pore geometry factor G vs. actual pore geometry factor G , a second graph 702 illustrating estimated fractional bulk volume Bv vs. actual fractional bulk volume Bv , and a third graph 704 illustrating estimated minimum entry pressure Pd vs. actual minimum entry pressure Pd . FIG. 7 also includes bar graphs that depict the distribution of the estimated Thomeer parameters as compared to the distribution of the actual Thomeer parameters obtained from a model database. As shown in FIG. 7, the figure includes a first bar graph 706 that depicts the distribution of estimated and actual pore geometry factor G , a second bar graph 708 that depicts the distribution of estimated and actual fractional bulk volume Bv , and a third bar graph 710 that depicts the distribution of estimated and actual minimum entry pressure Pd . As shown from these figures, the distribution of the estimated Thomeer parameters is consistent with the distribution of the actual Thomeer parameters. Additionally, as shown from these figures, the range for the Thomeer parameters is also consistent.

[0094] FIG. 8 depicts graphs of the estimated Thomeer parameters (G , Bv , and Pd) vs. the actual Thomeer parameters for a second pore system having $n = 2$. FIG. 8 depicts a first graph 800 illustrating estimated pore geometry factor G vs. actual pore geometry factor G , a second graph 802 illustrating estimated fractional bulk volume Bv vs. actual fractional bulk volume Bv , and a third graph 804 illustrating estimated minimum entry pressure Pd vs. actual minimum entry pressure Pd . As shown in FIG. 8, the figure also includes a first bar graph 806 that depicts the distribution of estimated and actual pore geometry factor G , a second bar graph 808 that depicts the distribution of estimated and actual fractional bulk volume Bv , and a third bar graph 810 that depicts the distribution of estimated and actual minimum entry pressure Pd . The figures illustrate a higher difficulty of estimation due to the insensitivity of the permeability to the pore system 2 characteristics. However, these figures show that a consistent trend for fractional bulk volume Bv is obtained as the porosity is sensitive to the Bv values for the three pore systems. For the minimum entry pressure Pd and the pore geometry factor G , the low sensitivity of the saturation to these two parameters increases the difficulty of their estimation and the optimization program may generate a solution consistent with the prior term included in the objective function. As shown in the bar graphs 806, 808, and 810, the prior term will control the consistency of these parameters' distributions.

[0095] FIG. 9 depicts graphs of the estimated Thomeer parameters (G , Bv , and Pd) vs. the actual Thomeer parameters for a second pore system having $n = 3$. FIG. 9 depicts a first

graph 900 illustrating estimated pore geometry factor G vs. actual pore geometry factor G , a second graph 902 illustrating estimated fractional bulk volume Bv vs. actual fractional bulk volume Bv , and a third graph 904 illustrating estimated minimum entry pressure Pd vs. actual minimum entry pressure Pd . The figures illustrate a higher difficulty of estimation due to the insensitivity of the permeability to the pore system characteristics. Here again, however, the graphs show a consistent trend for fractional bulk volume Bv as the porosity is sensitive to the Bv values for the three pore systems. Similarly, as noted above, the low sensitivity of the saturation to the minimum entry pressure Pd and the pore geometry factor G increases the difficulty of their estimation, and the optimization program may generate a solution consistent with the prior term included in the objective function. FIG. 9 also depicts a first bar graph 806 that depicts the distribution of estimated and actual pore geometry factor G , a second bar graph 808 that depicts the distribution of estimated and actual fractional bulk volume Bv , and a third bar graph 810 that depicts the distribution of estimated and actual minimum entry pressure Pd that depict the control the prior term of the objective function over the parameters' distributions.

[0096] FIG. 10 depicts the Thomeer parameters' distributions from for the model parameters and database parameters for the three pore systems discussed above and in accordance with an embodiment of the present invention. FIG. 10 illustrates the consistency between the modeled and actual Thomeer parameters and thus validates the utility of the capillary pressures derived from the Thomeer equation using Thomeer estimated according to the techniques described herein.

[0097] FIGS. 11-15 are plots of modeled data and actual data for the five synthetic wells used for the validation testing described above and in accordance with an embodiment of the present invention. Each plot includes: the match of the modeled porosity vs. the actual porosity data, the match of the modeled saturation vs. the actual saturation data; the match of the modeled permeability vs. the actual permeability data; the geometry factor G for the three pore systems; the bulk volume Bv for the three pore systems, and the minimum entry pressure Pd for the three pore systems. The plots illustrate that the techniques described estimate the Thomeer parameters for a multi-pore system that is consistent with the actual Thomeer parameters and well log data used for validation testing.

[0098] Further modifications and alternative embodiments of various aspects of the invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those

skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as examples of embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed or omitted, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims. Headings used herein are for organizational purposes only and are not meant to be used to limit the scope of the description.

[0099] As used throughout this application, the word “may” is used in a permissive sense (i.e., meaning having the potential to), rather than the mandatory sense (i.e., meaning must). The words “include”, “including”, and “includes” mean including, but not limited to. As used throughout this application, the singular forms “a”, “an” and “the” include plural referents unless the content clearly indicates otherwise. Thus, for example, reference to “an element” includes a combination of two or more elements. Unless specifically stated otherwise, as apparent from the discussion, it is appreciated that throughout this specification discussions utilizing terms such as “processing”, “computing”, “calculating”, “determining” or the like refer to actions or processes of a specific apparatus, such as a special purpose computer or a similar special purpose electronic processing/computing device. In the context of this specification, a special purpose computer or a similar special purpose electronic processing/computing device is capable of manipulating or transforming signals, typically represented as physical electronic or magnetic quantities within memories, registers, or other information storage devices, transmission devices, or display devices of the special purpose computer or similar special purpose electronic processing/computing device.

[00100] The present techniques will be better understood when considered in view of the following enumerated embodiments:

1) A computer-implemented method for determining capillary pressure in a reservoir, the method comprising:
accessing well log data from a well log for a well, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data;
determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data, the Thomeer parameters comprising a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure, the

determining comprising:

determining a modeled permeability;

determining a modeled porosity;

determining a modeled water saturation, and

evaluating an objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints, the objective function comprising:

$$F(T) = \frac{w}{2} \|(1 - S_{w_{FAL}}) - S_o(T)\|^2 + \frac{(1 - w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameters,

$S_{w_{FAL}}$ is the value of the water saturation data,

$S_o(T)$ is a modeled oil saturation;

the one or more linear equality constraints comprising:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury,

Pc is an applied capillary pressure;

α is the conversion factor from mercury-air to oil-water,

n is the number of pore systems in the reservoir,

ϕ_{FAL} is the porosity data;

the one or more linear inequality constraints comprising:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

If $Bv_i(Pc) \neq 0$ then $Bv_{i+1}(Pc) \leq Bv_i(Pc)$ for $1 \leq i \leq n-1$,

$Pd_i \leq Pd_{i+1}$ for $1 \leq i \leq n-1$, and

the one or more nonlinear equality constraints comprising:

$$K(T) = K_{FAL}$$

wherein $K(T)$ is the modeled permeability,

K_{FAL} is the permeability log data; and

determining the capillary pressure of the reservoir using a Thomeer model having the determined Thomeer parameters.

2) The computer-implemented method of embodiment 1, wherein the modeled permeability comprises:

$$K(T) = 506 * \sum_{i=1}^n \frac{Bv_i(Pc)}{Pd_i^2} \exp(-4.43\sqrt{G_i}).$$

3) The computer-implemented method of embodiments 1-2, wherein the modeled porosity comprises:

$$\phi(T) = \alpha \sum_{i=1}^n Bv_i.$$

4) The computer-implemented method of embodiment 1-3, wherein the modeled oil saturation comprises:

$$So_i(G_i, Pd_i) = Bv_i^\infty * \exp\left(\frac{-G_i}{\log(Pc) - \log(Pd_i)}\right); \text{ and}$$

$$So(T) = \frac{1}{\phi} \sum_{i=1}^n Bv_i * So_i(G_i, Pd_i).$$

5) The computer implemented method of embodiments 1-4, wherein the Thomeer model comprises:

$$B_v(P_c) \approx \begin{cases} \phi \cdot \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) & \text{for } P_c > P_d \\ 0 & \text{elsewhere} \end{cases}$$

6) The computer-implemented method of embodiments 1-5, wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function until convergence criteria are met.

7) The computer-implemented method of embodiments 1-6, wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality

constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function evaluating the objective function using sequential quadratic programming (SQP).

8) The computer-implemented method of embodiments 1-7, wherein the well log comprises a fluid analysis log.

9) The computer-implemented method of embodiments 1-8, wherein the reservoir comprises an oil reservoir.

10) The computer-implemented method of embodiments 1-9, comprising providing the capillary pressures to a reservoir modeling system, a reservoir simulation system, or a combination thereof.

11) A non-transitory tangible computer-readable storage medium having executable computer code stored thereon for determining capillary pressure in a reservoir, the computer code comprising a set of instructions that causes one or more processors to perform the following operations:

accessing well log data from a well log for a well, the well log data including permeability log data, porosity log data, water saturation log data, and oil saturation log data;

determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data, the Thomeer parameters comprising a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure, the determining comprising:

determining a modeled permeability;

determining a modeled porosity;

determining a modeled water saturation, and

evaluating an objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints, the objective function comprising:

$$F(T) = \frac{w}{2} \|(1 - S_{w_{FAL}}) - S_o(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameters,

$S_{w_{FAL}}$ is the value of the water saturation data,

$So(T)$ is a modeled oil saturation;

the one or more linear equality constraints comprising:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury,

Pc is an applied capillary pressure;

α is the conversion factor from mercury-air to oil-water,

n is the number of pore systems in the reservoir,

ϕ_{FAL} is the porosity data;

the one or more linear inequality constraints comprising:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

If $Bv_i(Pc) \neq 0$ then $Bv_{i+1}(Pc) \leq Bv_i(Pc)$ for $1 \leq i \leq n-1$,

$Pd_i \leq Pd_{i+1}$ for $1 \leq i \leq n-1$, and

the one or more nonlinear equality constraints comprising:

$$K(T) = K_{FAL}$$

wherein $K(T)$ is the modeled permeability,

K_{FAL} is the permeability log data; and

determining the capillary pressures of the reservoir using a Thomeer model having the determined Thomeer parameters.

12) The non-transitory tangible computer-readable storage medium of embodiment 11, wherein the modeled permeability comprises:

$$K(T) = 506 * \sum_{i=1}^n \frac{Bv_i(Pc)}{Pd_i^2} \exp(-4.43\sqrt{G_i}).$$

13) The non-transitory tangible computer-readable storage medium of embodiments 11-12, wherein the modeled porosity comprises:

$$\phi(T) = \alpha \sum_{i=1}^n Bv_i.$$

14) The non-transitory tangible computer-readable storage medium of embodiments 11-13, wherein the modeled oil saturation comprises:

$$So_i(G_i, Pd_i) = Bv_i^\infty * \exp\left(\frac{-G_i}{\log(P_c) - \log(Pd_i)}\right); \text{ and}$$

$$So(T) = \frac{1}{\phi} \sum_{i=1}^n Bv_i * So_i(G_i, Pd_i).$$

15) The non-transitory tangible computer-readable storage medium of embodiments 11-14, wherein the Thomeer model comprises:

$$B_v(P_c) \approx \begin{cases} \phi \cdot \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) & \text{for } P_c > P_d \\ 0 & \text{elsewhere} \end{cases}$$

16) The non-transitory tangible computer-readable storage medium of embodiments 11-15, wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function until convergence criteria are met.

17) The non-transitory tangible computer-readable storage medium of embodiments 11-16, wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function evaluating the objective function using sequential quadratic programming (SQP).

18) The non-transitory tangible computer-readable storage medium of embodiments 11-17, wherein the well log comprises a fluid analysis log.

19) The non-transitory tangible computer-readable storage medium of embodiments 11-18, wherein the reservoir comprises an oil reservoir.

20) A system for determining capillary pressure in a basin and reservoir, the system comprising:

well log data, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data;

one or more processors;

a tangible non-transitory computer-readable memory having executable computer code stored thereon for determining capillary pressure in a reservoir, the computer code comprising a set of instructions that causes the one or more processors to perform the following operations:

determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data, the Thomeer parameters comprising a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure, the determining comprising:

evaluating an objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints, the objective function comprising:

$$F(T) = \frac{w}{2} \|(1 - S_{w_{FAL}}) - So(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameters,

$S_{w_{FAL}}$ is the value of the water saturation data,

$So(T)$ is a modeled oil saturation;

the one or more linear equality constraints comprising:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury,

Pc is an applied capillary pressure;

α is the conversion factor from mercury-air to oil-water,

n is the number of pore systems in the reservoir,

ϕ_{FAL} is the porosity data;

the one or more linear inequality constraints comprising:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

If $Bv_i(Pc) \neq 0$ then $Bv_{i+1}(Pc) \leq Bv_i(Pc)$ for $1 \leq i \leq n-1$,

$Pd_i \leq Pd_{i+1}$ for $1 \leq i \leq n-1$, and

the one or more nonlinear equality constraints comprising:

$$K(T) = K_{FAL}$$

wherein $K(T)$ is the modeled permeability,

K_{FAL} is the permeability log data; and

determining the capillary pressures of the reservoir using a Thomeer model having the determined Thomeer parameters.

21) The system of embodiments 20, tangible non-transitory computer-readable memory storing a modeled permeability, a modeled porosity, and a modeled water saturation.

22) The system of embodiments 21, wherein the modeled permeability comprises:

$$K(T) = 506 * \sum_{i=1}^n \frac{Bv_i(Pc)}{Pd_i^2} \exp(-4.43\sqrt{G_i}).$$

23) The system of embodiment 21, wherein the modeled porosity comprises:

$$\phi(T) = \alpha \sum_{i=1}^n Bv_i.$$

24) The system of embodiment 21, wherein the modeled oil saturation comprises:

$$So_i(G_i, Pd_i) = Bv_i^\infty * \exp\left(\frac{-G_i}{\log(Pc) - \log(Pd_i)}\right); \text{ and}$$

$$So(T) = \frac{1}{\phi} \sum_{i=1}^n Bv_i * So_i(G_i, Pd_i).$$

25) The system of embodiment 20, the tangible non-transitory computer-readable memory storing a Thomeer model, the Thomeer model comprising:

$$B_v(P_c) \approx \begin{cases} \phi \cdot \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) & \text{for } P_c > P_d \\ 0 & \text{elsewhere} \end{cases}$$

26) The system of embodiments 20-25, wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function until convergence criteria are met.

27) The system of embodiments 20-26, wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function evaluating the objective function using sequential quadratic programming (SQP).

28) The system of embodiments 20-27, wherein the well log comprises a fluid analysis log.

29) The system of embodiments 20-28, wherein the reservoir comprises an oil reservoir.

30) The system of embodiments 20-29, comprising a network coupled to the one or more processor.

31) The system of embodiments 20-30, comprising providing, over the network, the capillary pressures to a reservoir modeling system, a reservoir simulation system, or a combination thereof.

32) A computer-implemented method for determining capillary pressure in a reservoir, the method comprising:

accessing well log data from a well log for a well, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data;

evaluating an objective function measuring the different between the permeability log data and a modeled permeability, the porosity log data and a modeled porosity, and the oil saturation log data and a modeled oil saturation, the modeled permeability, the modeled porosity, and the modeled oil saturation each a function of Thomeer parameters; and

determining the capillary pressures of the reservoir using a Thomeer model having the Thomeer parameters, the Thomeer parameters comprising a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure for each pore system.

33) The computer-implemented method of embodiment 32, wherein evaluating the objective function measuring the different between the permeability log data and a modeled permeability, the porosity log data and a modeled porosity, and the oil saturation log data and a modeled oil saturation comprises evaluating the objective function based on a linear equality constraint dependent on the porosity log data, a linear inequality constraint, and a nonlinear equality constraint dependent on the permeability log data.

CLAIMS

What is claimed is:

1. A computer-implemented method for determining capillary pressure in a reservoir, the method comprising:
 accessing well log data from a well log for a well, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data;
 determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data, the Thomeer parameters comprising a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure, the determining comprising:
 determining a modeled permeability;
 determining a modeled porosity;
 determining a modeled water saturation, and
 evaluating an objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints, the objective function comprising:

$$F(T) = \frac{w}{2} \left\| (1 - S_{w_{FAL}}) - S_o(T) \right\|^2 + \frac{(1-w)}{2} \left\| T - \hat{T} \right\|^2$$

wherein T is the Thomeer parameters,

$S_{w_{FAL}}$ is the value of the water saturation data,

$S_o(T)$ is a modeled oil saturation;

the one or more linear equality constraints comprising:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury,

Pc is an applied capillary pressure;

α is the conversion factor from mercury-air to oil-water,

n is the number of pore systems in the reservoir,

ϕ_{FAL} is the porosity data;

the one or more linear inequality constraints comprising:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

$$\text{If } Bv_i(Pc) \neq 0 \text{ then } Bv_{i+1}(Pc) \leq Bv_i(Pc) \text{ for } 1 \leq i \leq n-1,$$

$$Pd_i \leq Pd_{i+1} \text{ for } 1 \leq i \leq n-1, \text{ and}$$

the one or more nonlinear equality constraints comprising:

$$K(T) = K_{FAL}$$

wherein $K(T)$ is the modeled permeability,

K_{FAL} is the permeability log data; and

determining the capillary pressure of the reservoir using a Thomeer model having the determined Thomeer parameters.

2. The computer-implemented method of claim 1, wherein the modeled permeability comprises:

$$K(T) = 506 * \sum_{i=1}^n \frac{Bv_i(Pc)}{Pd_i^2} \exp(-4.43\sqrt{G_i}).$$

3. The computer-implemented method of claim 1 or 2, wherein the modeled porosity comprises:

$$\phi(T) = \alpha \sum_{i=1}^n Bv_i.$$

4. The computer-implemented method of claim 1, 2, or 3 wherein the modeled oil saturation comprises:

$$So_i(G_i, Pd_i) = Bv_i^\omega * \exp\left(\frac{-G_i}{\log(Pc) - \log(Pd_i)}\right); \text{ and}$$

$$So(T) = \frac{1}{\phi} \sum_{i=1}^n Bv_i * So_i(G_i, Pd_i).$$

5. The computer implemented method of claim 1, 2, 3, or 4, wherein the Thomeer model comprises:

$$B_v(P_c) \approx \begin{cases} \phi \cdot \exp\left(\frac{-G}{\log(P_c) - \log(P_d)}\right) & \text{for } P_c > P_d \\ 0 & \text{elsewhere} \end{cases}$$

6. The computer-implemented method of claim 1, 2, 3, 4, or 5 wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function until convergence criteria are met.
7. The computer-implemented method of claim 1, 2, 3, 4, 5, or 6 wherein evaluating the objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints comprises iteratively evaluating the objective function evaluating the objective function using sequential quadratic programming (SQP).
8. The computer-implemented method of claim 1, 2, 3, 4, 5, 6, or 7 wherein the well log comprises a fluid analysis log.
9. The computer-implemented method of claim 1, 2, 3, 4, 5, 6, 7, or 8 wherein the reservoir comprises an oil reservoir.
10. The computer-implemented method of claim 1, 2, 3, 4, 5, 6, 7, 8, or 9 comprising providing the capillary pressures to a reservoir modeling system, a reservoir simulation system, or a combination thereof.
11. A computer program comprising computer program code means adapted to perform all the steps of any of claims 1 to 10 when said program is run on a computer.
12. A computer program as claimed in claim 11 embodied on a computer readable medium.

13. A system for determining capillary pressure in a basin and reservoir, the system comprising:
 well log data, the well log data comprising permeability log data, porosity log data, water saturation log data, and oil saturation log data;
 one or more processors;
 a tangible non-transitory computer-readable memory having executable computer code stored thereon for determining capillary pressure in a reservoir, the computer code comprising a set of instructions that causes the one or more processors to perform the following operations:

determining Thomeer parameters from the permeability log data, the porosity log data, the water saturation log data, and the oil saturation log data, the Thomeer parameters comprising a fractional bulk volume, a pore geometrical factor, and a minimum entry pressure, the determining comprising:

evaluating an objective function based on one or more linear equality constraints, one or more linear inequality constraints, and one or more nonlinear equality constraints, the objective function comprising:

$$F(T) = \frac{w}{2} \|(1 - S_{W_{FAL}}) - S_o(T)\|^2 + \frac{(1-w)}{2} \|T - \hat{T}\|^2$$

wherein T is the Thomeer parameters,

$S_{W_{FAL}}$ is the value of the water saturation data,

$S_o(T)$ is a modeled oil saturation;

the one or more linear equality constraints comprising:

$$\sum_{i=1}^n Bv_i(Pc) = \alpha * \phi_{FAL}$$

wherein Bv_i is a fractional bulk volume occupied by mercury,

Pc is an applied capillary pressure;

α is the conversion factor from mercury-air to oil-water,

n is the number of pore systems in the reservoir,

ϕ_{FAL} is the porosity data;

the one or more linear inequality constraints comprising:

$$Bv_i^{\min} \leq Bv_i(Pc) \leq Bv_i^{\max} \text{ for } 1 \leq i \leq n$$

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein G_i is the pore geometrical factor,

$$Pd_i^{\min} \leq Pd_i \leq Pd_i^{\max} \text{ for } 1 \leq i \leq n$$

wherein Pd_i is a minimum entry pressure,

If $Bv_i(Pc) \neq 0$ then $Bv_{i+1}(Pc) \leq Bv_i(Pc)$ for $1 \leq i \leq n-1$,

$Pd_i \leq Pd_{i+1}$ for $1 \leq i \leq n-1$, and

the one or more nonlinear equality constraints comprising:

$$K(T) = K_{FAL}$$

wherein $K(T)$ is the modeled permeability,

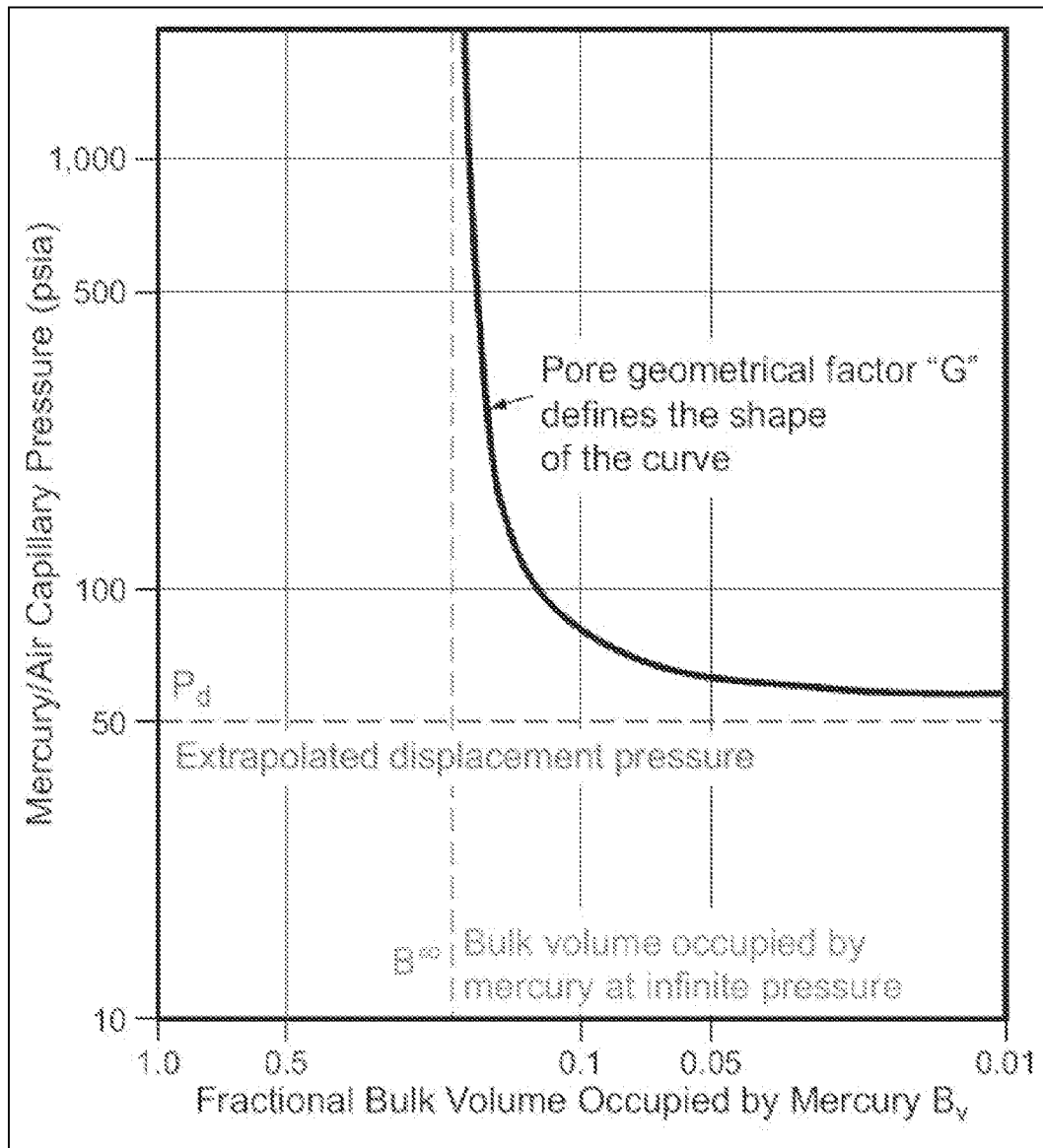
K_{FAL} is the permeability log data; and

determining the capillary pressures of the reservoir using a Thomeer model having the determined Thomeer parameters.

14. The system of claim 13, tangible non-transitory computer-readable memory storing a modeled permeability, a modeled porosity, and a modeled water saturation.

15. The system of claim 14, wherein the modeled permeability comprises:

$$K(T) = 506 * \sum_{i=1}^n \frac{Bv_i(Pc)}{Pd_i^2} \exp(-4.43\sqrt{G_i}).$$

**FIG. 1**

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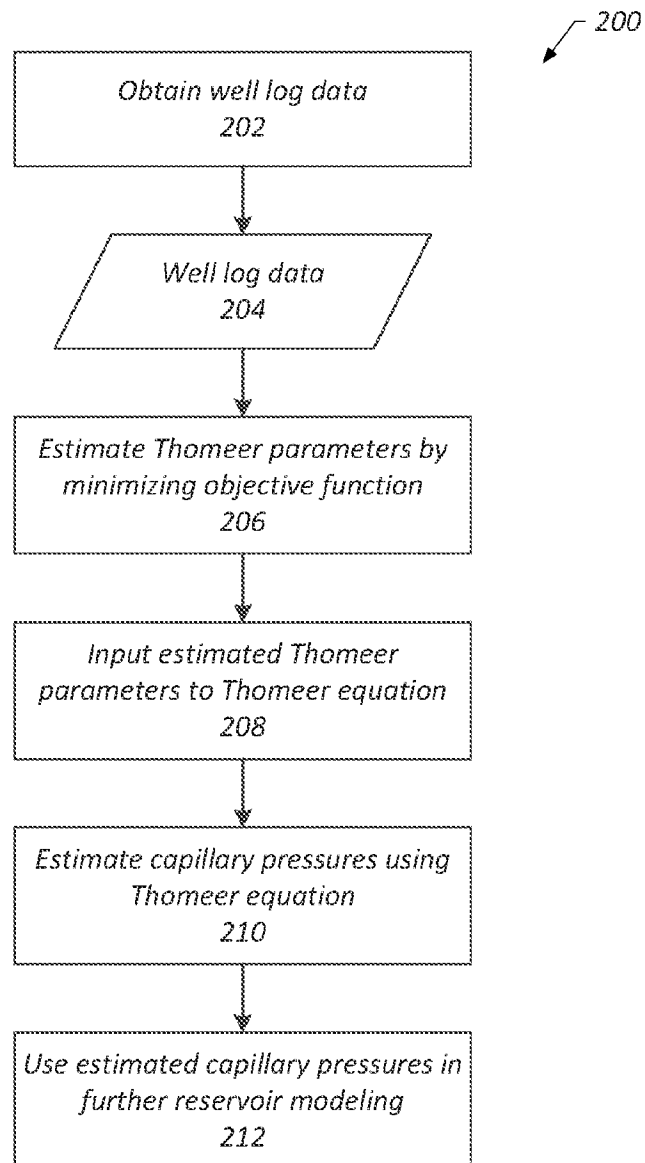


FIG. 2

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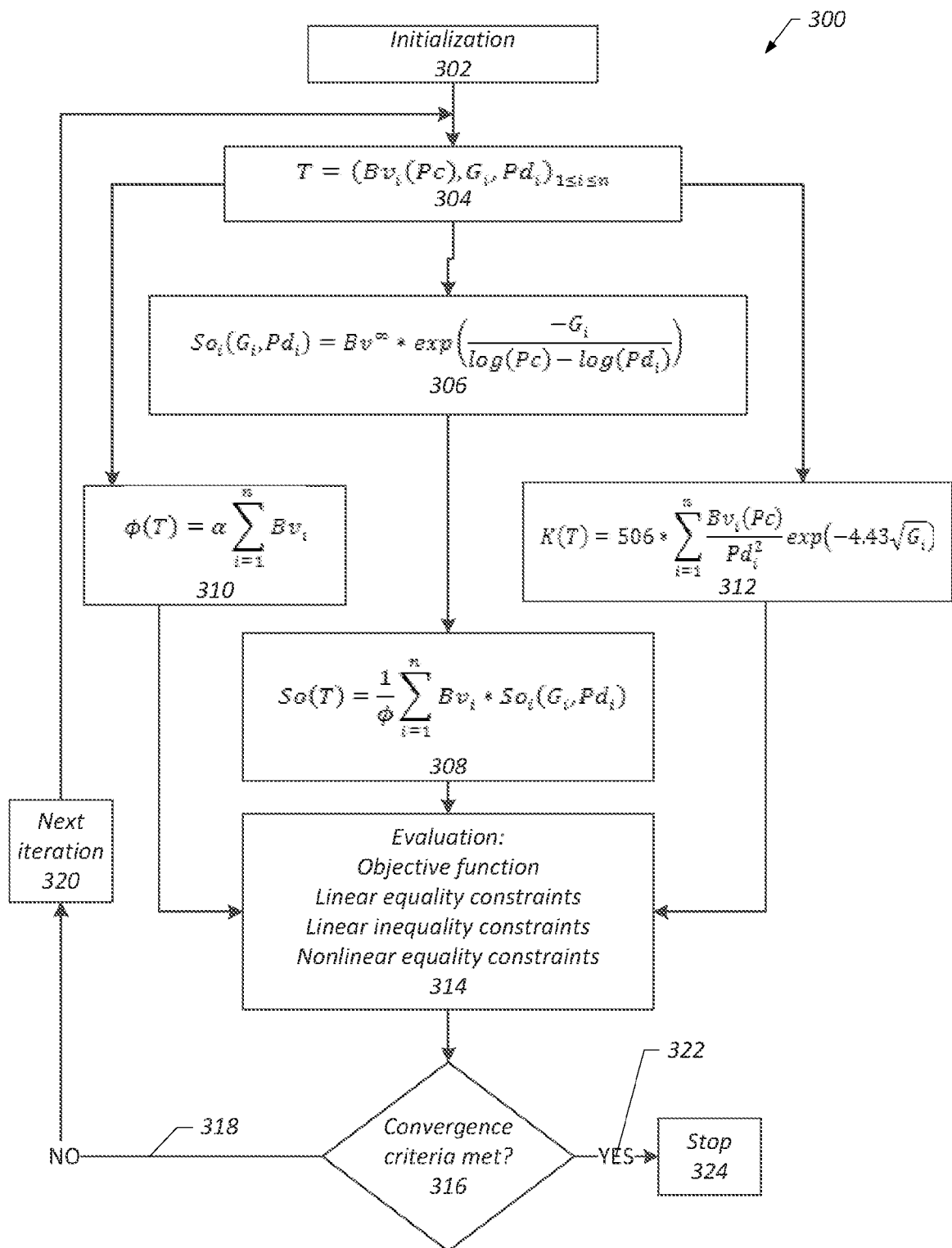


FIG. 3

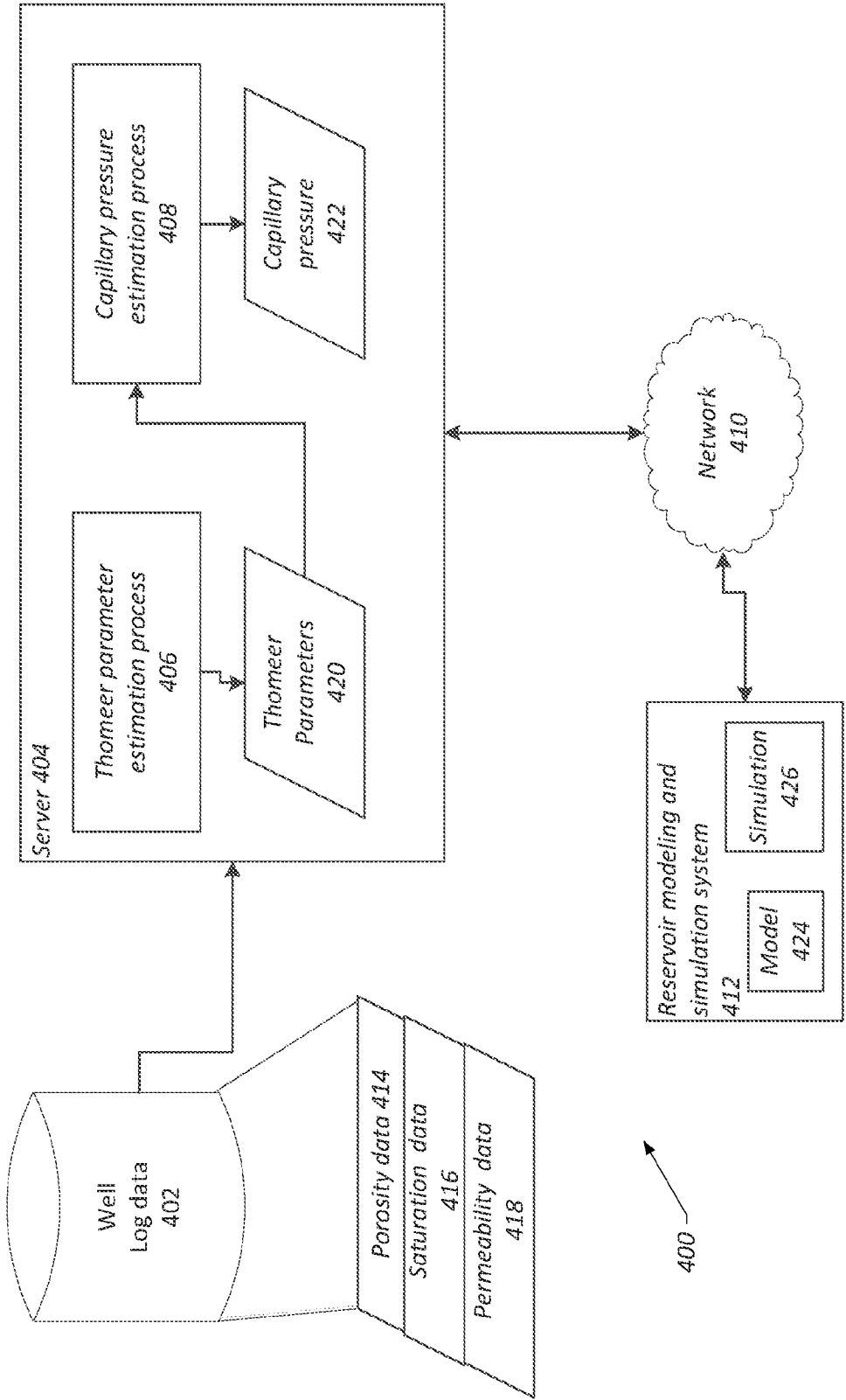


FIG. 4

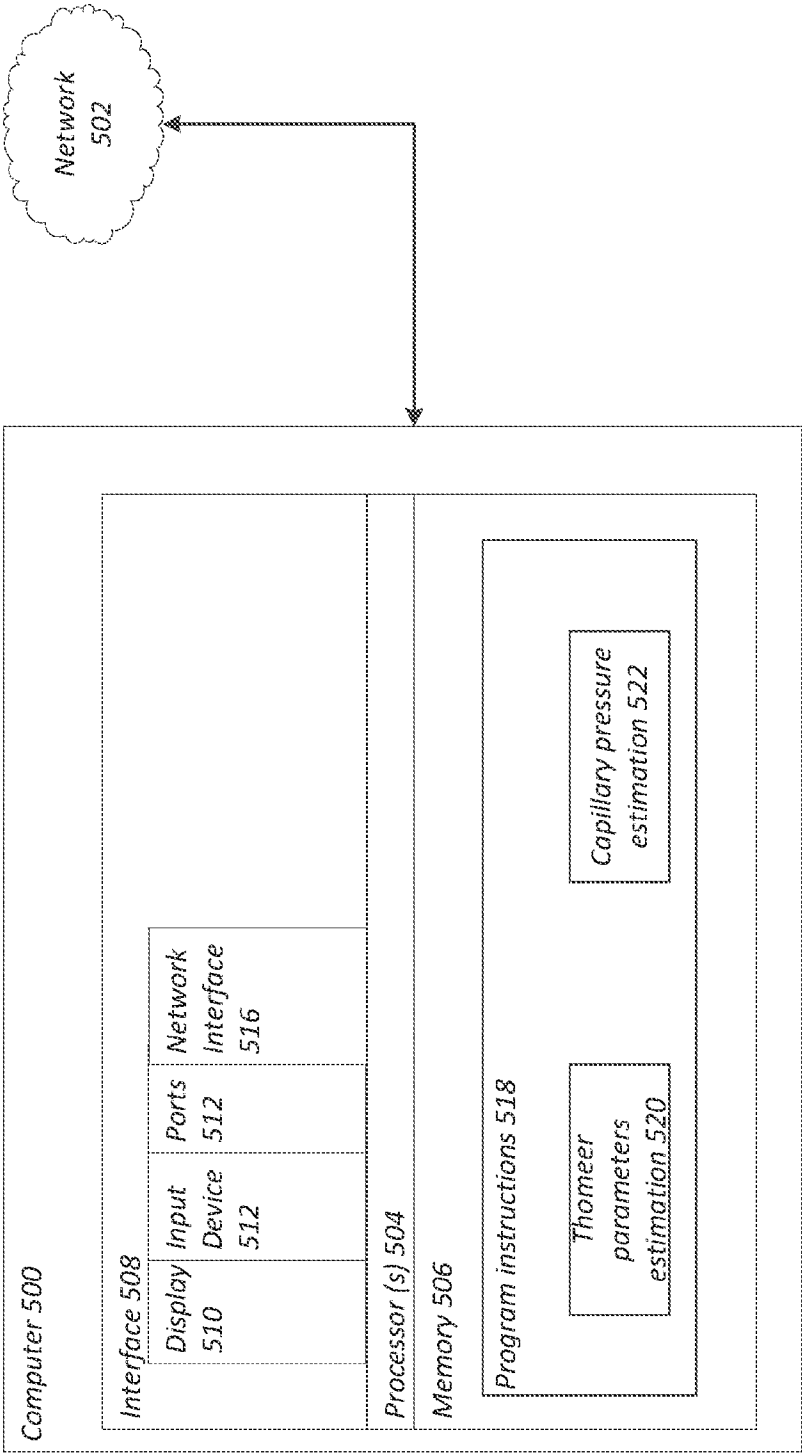


FIG. 5

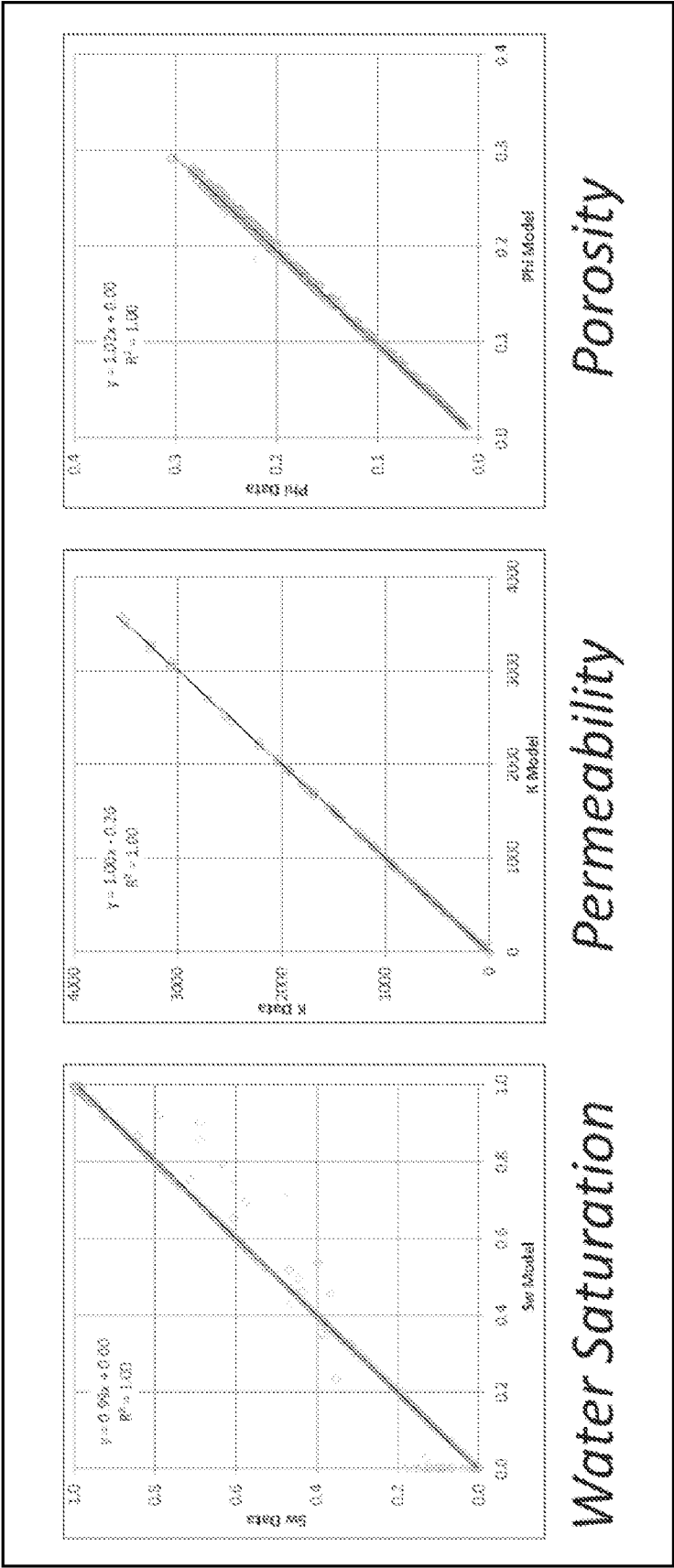


FIG. 6

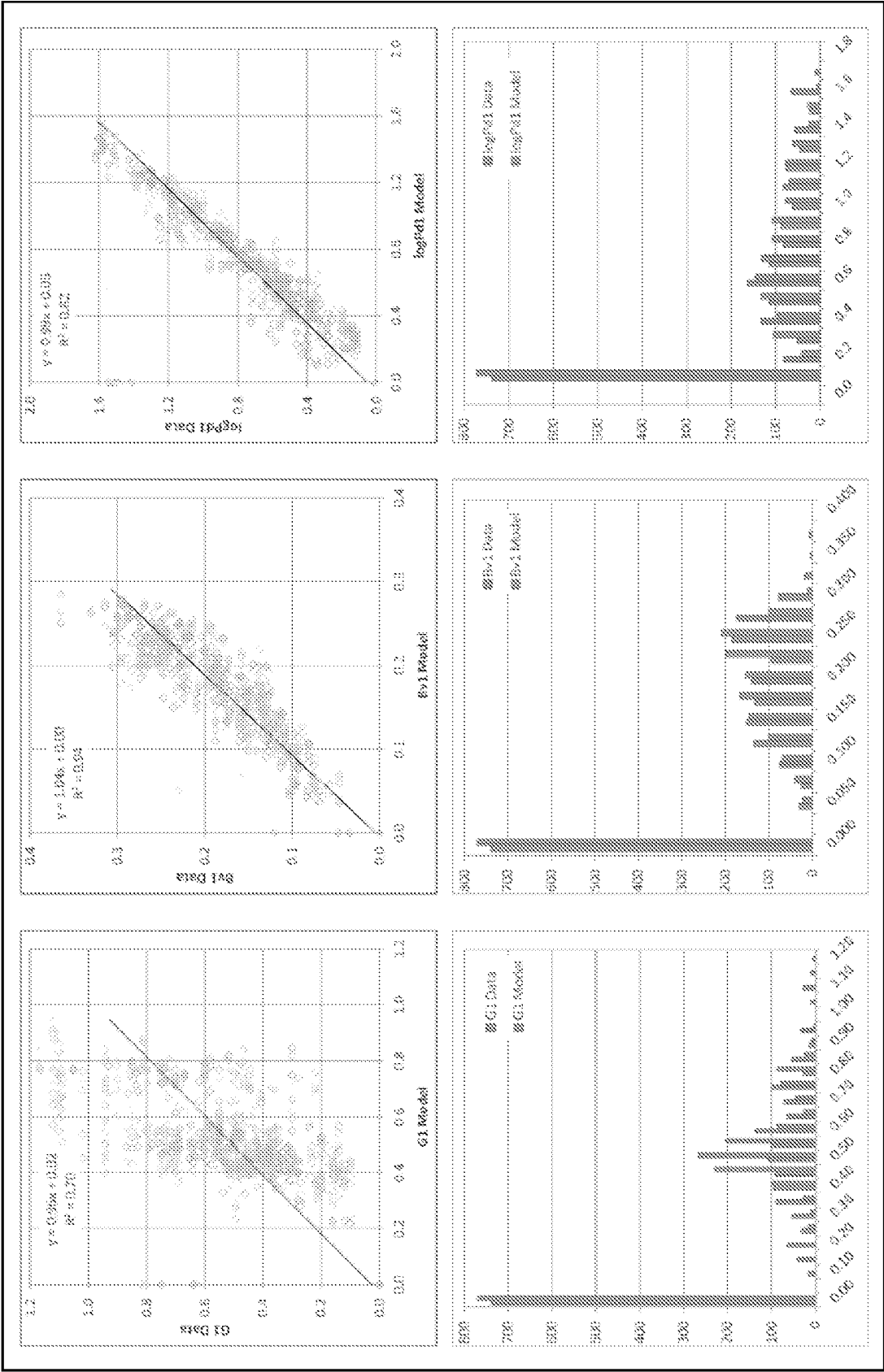


FIG. 7

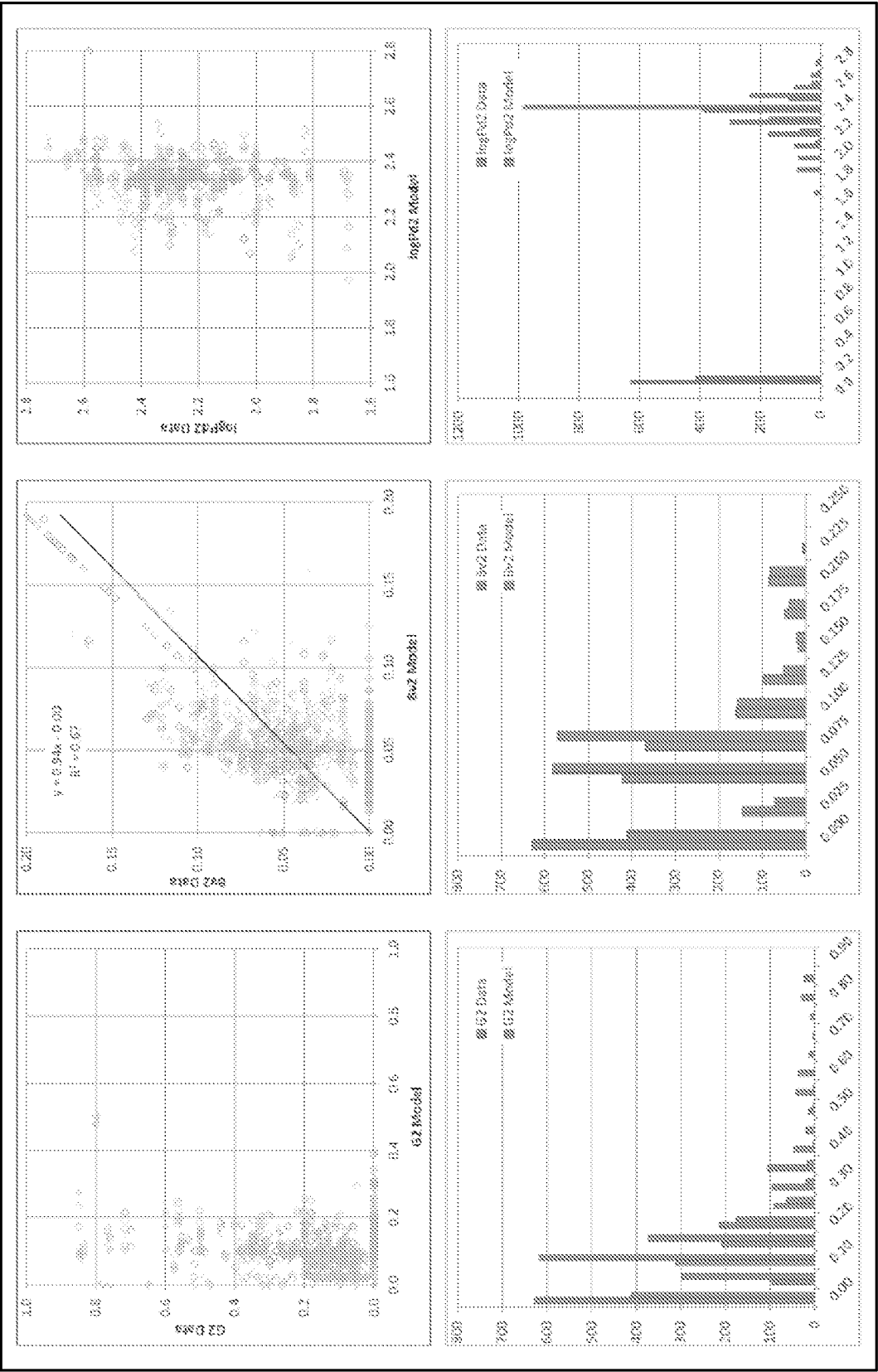


FIG. 8

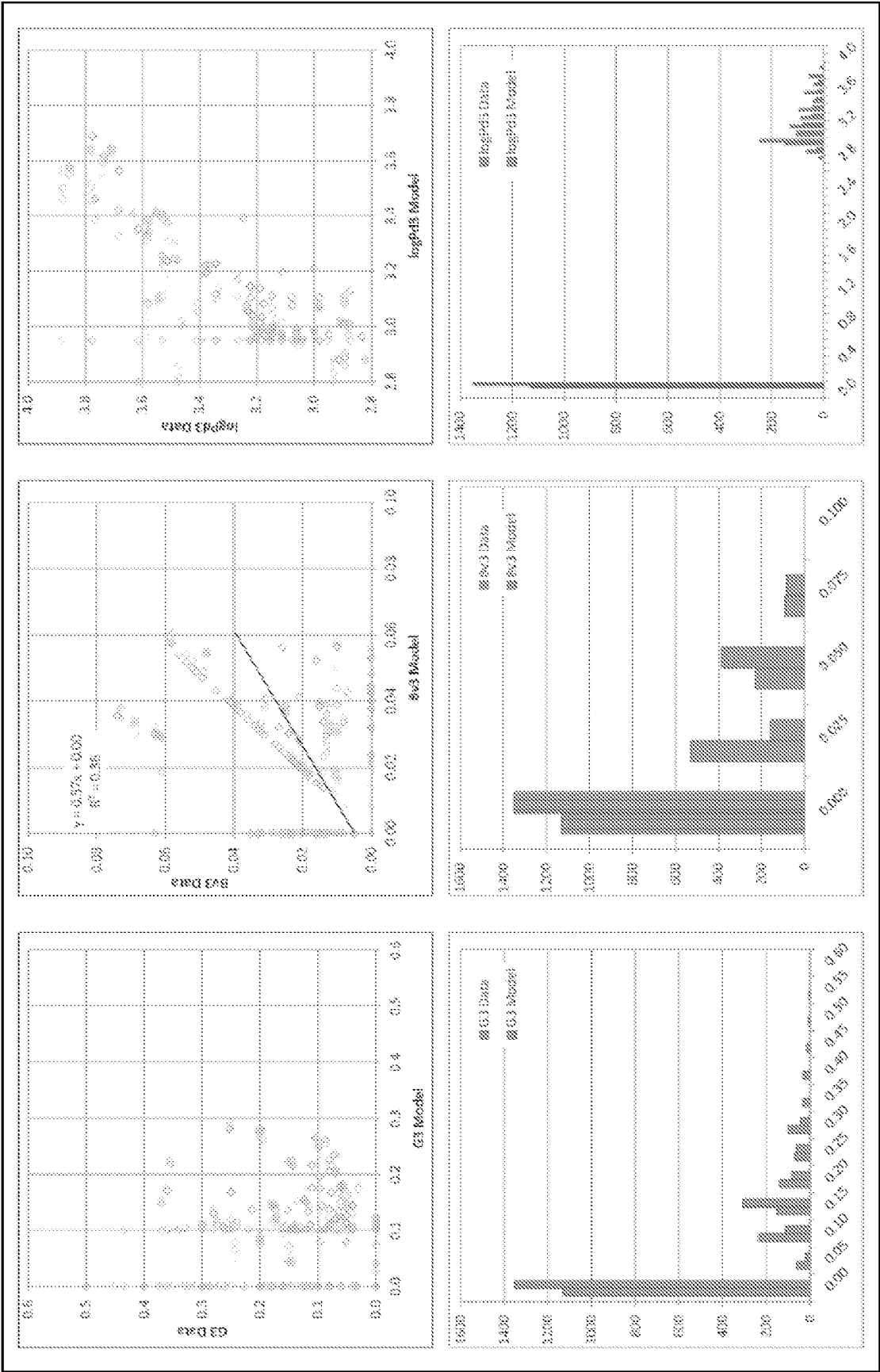


FIG. 9

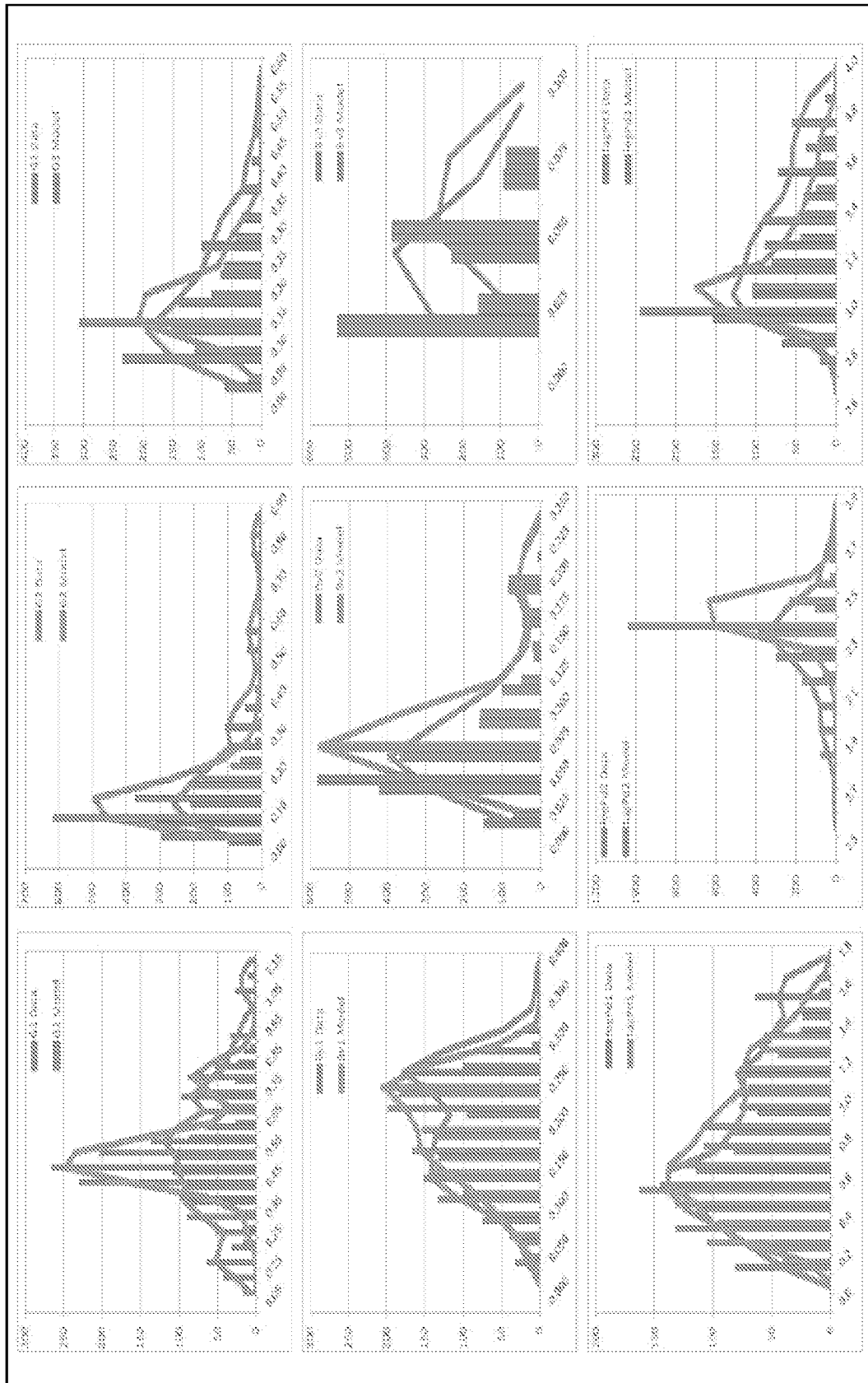


FIG. 10

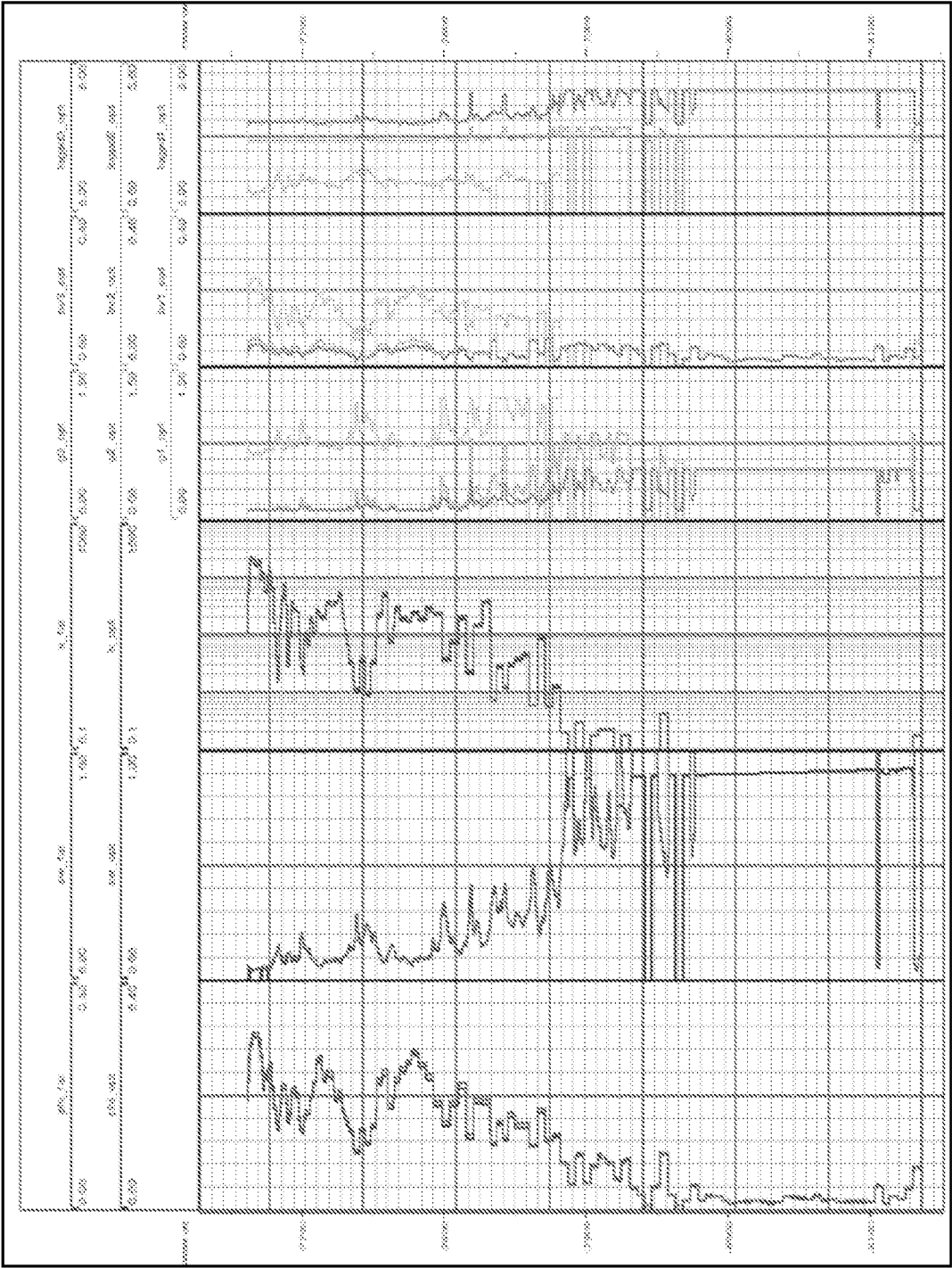


FIG. 11

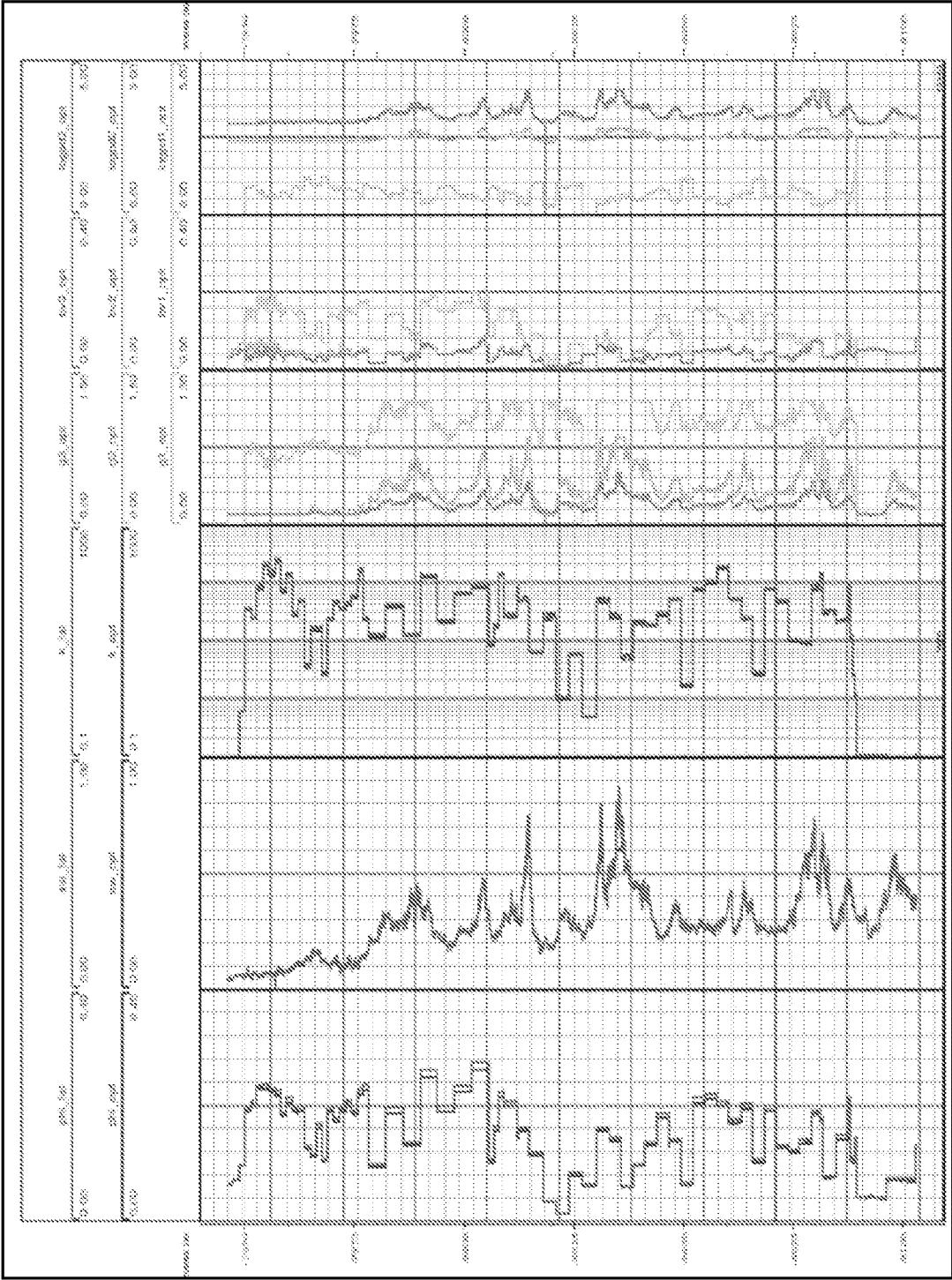


FIG. 12

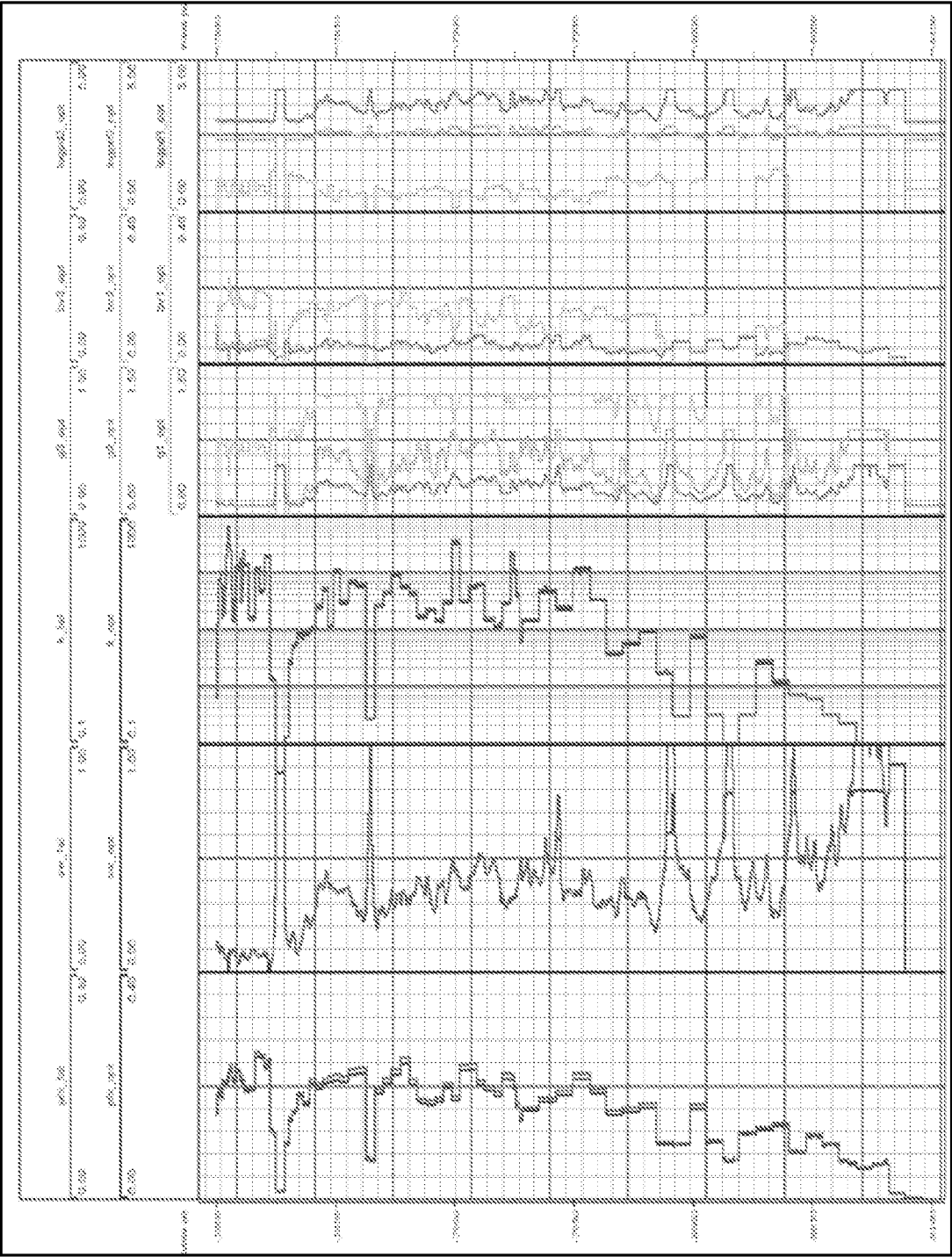


FIG. 13

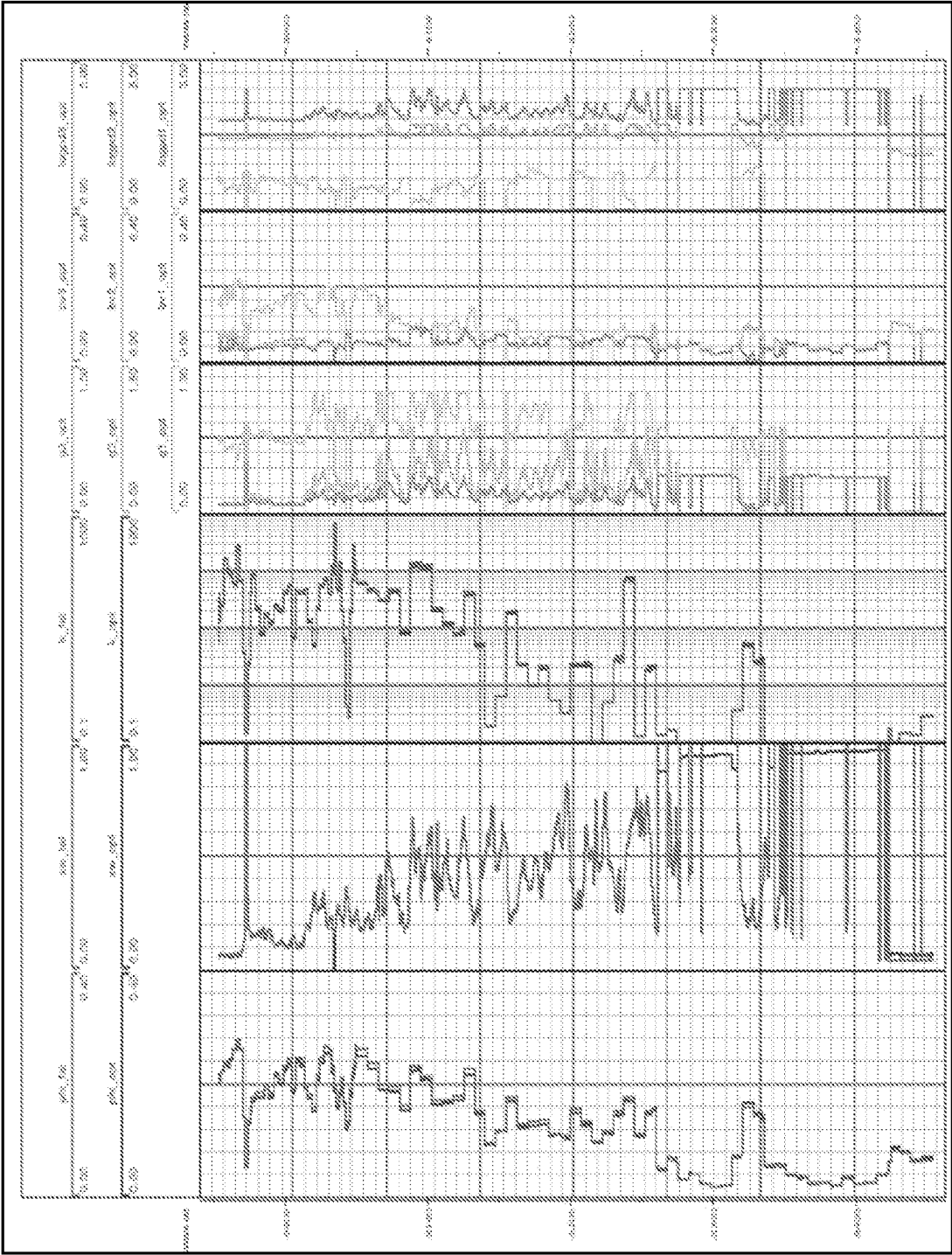


FIG. 14

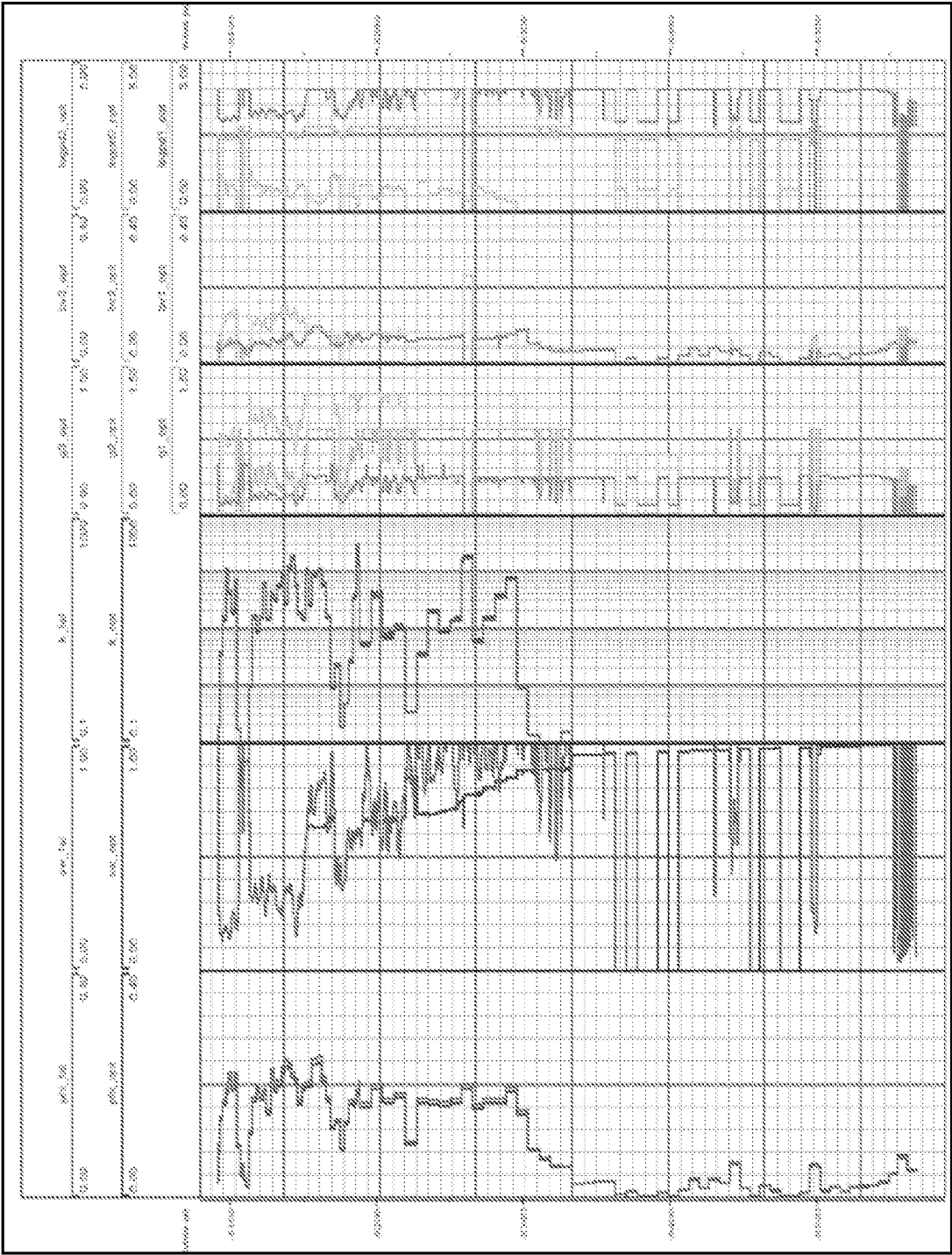


FIG. 15