Innovation, Sciences et
Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and
Economic Development Canada
Canadian Intellectual Property Office

CA 3134777 A1 2020/10/01

(21) **3 134 777**

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) **A1**

(86) **Date de dépôt PCT/PCT Filing Date:** 2020/03/25
(87) **Date publication PCT/PCT Publication Date:** 2020/10/01
(85) **Entrée phase nationale/National Entry:** 2021/09/23
(86) **N° demande PCT/PCT Application No.:** US 2020/024577
(87) **N° publication PCT/PCT Publication No.:** 2020/198284
(30) **Priorité/Priority:** 2019/03/26 (US16/365,217)

(51) **Cl.Int./Int.Cl.** *G01V 99/00* (2009.01),
G06F 30/20 (2020.01)
(71) **Demandeur/Applicant:**
SAUDI ARABIAN OIL COMPANY, SA
(72) **Inventeurs/Inventors:**
LI, YUPENG, CN;
MEZGHANI, MOKHLES MUSTAPHA, SA
(74) **Agent:** SMART & BIGGAR LLP

(54) **Titre :** ETALONNAGE AUTOMATIQUE DE MODELES DE DEPOT VERS L'AVANT
(54) **Title:** AUTOMATIC CALIBRATION OF FORWARD DEPOSITIONAL MODELS

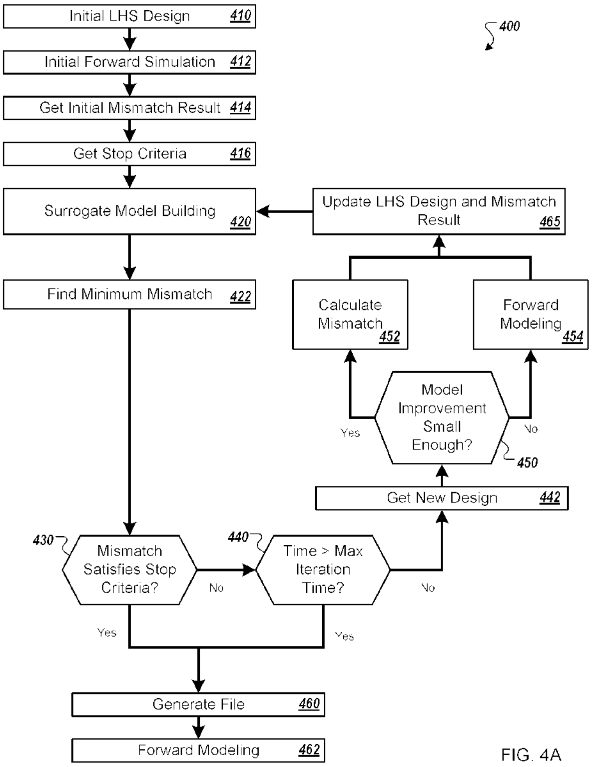

FIG. 4A

(57) **Abrégé/Abstract:**

The subject matter of this specification can be embodied in, among other things, a method for geological modeling includes receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transform the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical value, and determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
01 October 2020 (01.10.2020)

(10) International Publication Number
WO 2020/198284 A1

(51) International Patent Classification:
G01V 99/00 (2009.01) *G06F 30/20* (2020.01)

(21) International Application Number:
PCT/US2020/024577

(22) International Filing Date:
25 March 2020 (25.03.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
16/365,217 26 March 2019 (26.03.2019) US

(71) Applicant: SAUDI ARABIAN OIL COMPANY [SA/SA]; 1 Eastern Avenue, Dhahran, 31311 (SA).

(71) Applicant *(for AG only)*: **ARAMCO SERVICES COMPANY** [US/US]; 1200 Smith Street, Two Allen Building, Houston, Texas 77002 (US).

(72) Inventors: LI, Yupeng; 6/F, Kechuang Innovation Building, No. 4 Wangjing East Road, Chaoyang District, Beijing, 100102 (CN). **MEZGHANI, Mokhles Mustapha**; Saudi Aramco, P.O. Box 13765, Dhahran, 31311 (SA).

(74) Agent: BRUCE, Carl E. et al.; FISH & RICHARDSON P.C., P.O. Box 1022, Minneapolis, Minnesota 55440-1022 (US).

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

(54) Title: AUTOMATIC CALIBRATION OF FORWARD DEPOSITIONAL MODELS

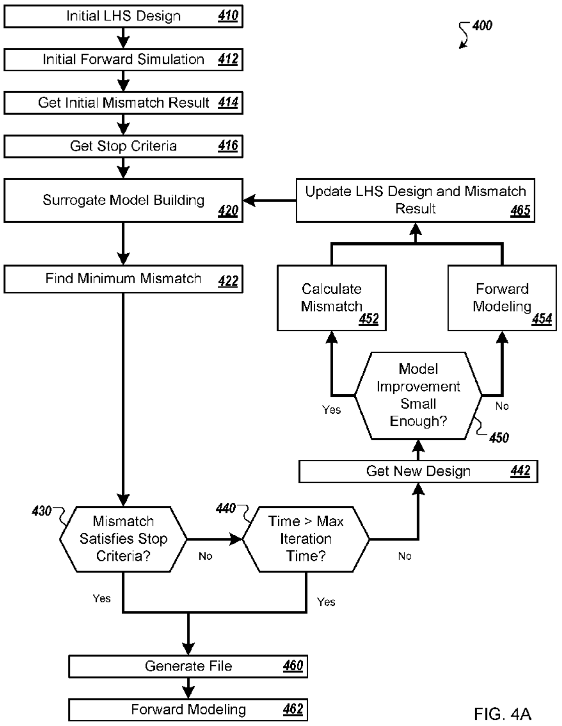

FIG. 4A

(57) Abstract: The subject matter of this specification can be embodied in, among other things, a method for geological modeling includes receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transform the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical value, and determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

WO 2020/198284 A1

[Continued on next page]

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

Published:

— *with international search report (Art. 21(3))*

AUTOMATIC CALIBRATION OF FORWARD DEPOSITIONAL MODELS

CLAIM OF PRIORITY

[0001] This application claims priority to U.S. Patent Application No. 16/365,217 filed on March 26, 2019, the entire contents of which are hereby incorporated by reference.

TECHNICAL FIELD

[0002] This instant specification relates to techniques for predicting subterranean geological structures.

BACKGROUND

[0003] A forward depositional modeling process usually includes several coupled or sequential sub-processes to simulate different depositional processes. Such a modeling procedure can numerically simulate fluid flow, sedimentation laws which govern erosion, transport, and deposition. Some sedimentation processes such as compaction and porosity reduction, fold deformation, diagenesis and fluid maturation can also be numerically simulated in the forward depositional modeling procedure.

[0004] The output of the numerical forward depositional simulation can be the stratigraphic spatial architectures, such as the thickness of each formation, and the lithology or the geological facies within each formation. The petrophysical properties of the simulated area, such as porosity and permeability can also be derived in the final model.

SUMMARY

[0005] In general, this document describes techniques for predicting subterranean geological structures.

[0006] In a first aspect, a method for geological modeling includes receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transform the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical value, and determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

[0007] Various implementations can include some, all, or none of the following features. The forward depositional model can be based on well log data descriptive of a drilled well path through a predetermined geographical area. The method can also include receiving the well log data descriptive of the drilled well path through the predetermined geographical area, and projecting, based on the well log data, the drilled well path to forward depositional model coordinates in the forward depositional model. The collection of simulated physical values can include a collection of at least one of hydraulic values, geological values, and sedimentological values. The method can also include determining a drilling path based on an identified set of predetermined input parameters, and drilling a well based on the determined drilling path. Determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value. Determining the kriging surrogate model can include determining a collection of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters, determining a collection of approximation models that are emulative of the collection of simulated models, ranking the collection of approximation models based on a comparison of each approximation model to the forward depositional model, and identifying, based on the ranking, an approximation model of the collection of approximation models that is emulative of the surrogate model. Determining a collection of simulated models based on the LHS stratigraphic model and a collection of forward depositional model parameters includes determining kriging predictions for locations not included in the forward depositional model.

[0008] In a second aspect, a system for geographical modeling includes a control system having one or more processors, and a non-transitory computer-readable medium storing instructions executable by the one or more processors to perform operations including receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transform the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values, and determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

[0009] Various embodiments can include some, all, or none of the following features. The system can also include determining a drilling path based on an identified set of predetermined input parameters, and drilling a well based on the determined drilling path. Determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value. Determining the kriging surrogate model can include determining a collection of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters, determining a collection of approximation models that are emulative of the collection of simulated models, ranking the collection of approximation models based on a comparison of each approximation model to the forward depositional model, and identifying, based on the ranking, an approximation model of the collection of approximation models that is emulative of the surrogate model. Determining a collection of simulated models based on the LHS stratigraphic model and a collection of forward depositional model parameters includes determining kriging predictions for locations not included in the forward depositional model.

[0010] In a third aspect, a non-transitory computer-readable medium storing instructions executable by a processing device to perform operations includes receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transforming the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values, determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

[0011] Various embodiments can include some, all, or none of the following features. The forward depositional model can be based on well log data descriptive of a drilled well path through a predetermined geographical area. The operations can also include receiving the well log data descriptive of the drilled well path through the predetermined geographical area, and projecting, based on the well log data, the drilled well path to forward depositional model coordinates in the forward depositional model. The operations can also include determining a drilling path based on an identified set of predetermined input parameters, and drilling a well based on the determined drilling path. Determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can also include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values including differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value. Determining the kriging surrogate model can include determining a collection of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters, determining a collection of approximation models that are emulative of the collection of simulated models, ranking the collection of approximation models based on a comparison of each approximation model to the forward depositional model, and identifying, based on the ranking, an approximation model of the collection of approximation models that is emulative of the surrogate model. Determining a collection of simulated models based on the LHS stratigraphic model and a collection of forward depositional model parameters can include determining kriging predictions for locations not included in the forward depositional model.

[0012] The systems and techniques described here may provide one or more of the following advantages. First, a system can provide models of subterranean geological structures that accurately reflect observed conditions. Second, the system can perform the modeling using relatively fewer computing resources than previous techniques. Third, the system can perform the modeling more quickly than previous techniques. Fourth, the system can provide information that can increase the efficiency of drilling operations.

[0013] The details of one or more implementations are set forth in the accompanying drawings and the description to be presented. Other features and advantages will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

[0014] FIG. 1 is an example cross-sectional view of an example depositional environment.

[0015] FIG. 2 shows a table of several example designs of input variables.

[0016] FIG. 3 shows three examples of simulated models.

[0017] FIG. 4A is a flow diagram of an example inverse depositional modeling workflow.

[0018] FIG. 4B shows example conceptual models of example stratigraphic realizations.

[0019] FIG. 4C shows an example conceptual mathematical representation of a surrogate model.

[0020] FIG. 4D shows an example surrogate model represented as a mathematical surface.

[0021] FIG. 5 is a flow diagram of an example Latin Hypercube sampling and physical transformation process.

[0022] FIG. 6A is a flow diagram of an example spatial depth transformation process.

[0023] FIG. 6B show example two and three-dimensional projections of example well trajectories.

[0024] FIG. 7A is a flow diagram of an example mismatch determination process.

[0025] FIG. 7B shows a graphical example of a time to spatial transformation of a model.

[0026] FIG. 7C shows an example grid values in a spatial transformation of a model.

[0027] FIGs. 8 and 9 are flow diagrams of example mismatch determination processes.

[0028] FIG. 10 is a flow diagram of an example parameter set generation process.

[0029] FIG. 11 is a flow diagram of an example process for calibration of forward depositional models.

DETAILED DESCRIPTION

[0030] This document describes systems and techniques for Inverse Depositional Modeling (IDM) using a kriging surrogate model based on optimization approach. The IDM method calibrates forward depositional model

(FDM) to prior observed data, which is expressed as well log data and is used as a constraint to the FDM. The following discussion describes techniques for the fitting of FDM to observations through a fast and automatic adjustment of the FDM input parameters.

[0031] One of the challenges of some forward depositional modeling approaches is to optimize the various input parameters such that the simulated output would maximally match available prior observed data (such as from the data logs obtained from physical drilling operations). This document describes techniques for finding sets of appropriate input parameters, including the initial and boundary conditions that can provide consistency between the simulated deposits and prior observed data.

[0032] The proposed approach described in this document can be applied to various specific forward depositional modeling approaches that could be treated as a “black-box” in the inverse procedure. Implementing a kriging surrogate based optimization approach can achieves faster computing compared to previous techniques.

[0033] A forward depositional modeling process usually includes several coupled or sequential sub-processes to simulate different depositional processes. Such modeling procedures can numerically simulate things such as fluid flows, sedimentation laws that govern erosion, transport, and deposition. Some sedimentation processes, such as compaction, porosity reduction, fold deformation, diagenesis and fluid maturation, can also be numerically simulated in the forward depositional modeling process.

[0034] The output of numerical forward depositional simulation can be the stratigraphic spatial architectures (such as the thickness of each formation), the lithology, or the geological facies within formations. In some implementations, the petrophysical properties of a simulated area, such as porosity and permeability, can also be derived.

[0035] FIG. 1 is an example cross-sectional view of an example depositional environment 100. The experimental depositional environment is a carbonate depositional environment. In some examples, a useful parameter for a forward depositional simulation is the growth rate of each rock type. In the current example, there are four rock types (facies) identified, which are lagoon 110, bank crest 120, algal platform 130, and deeper open marine 140.

[0036] For a forward depositional simulation process, the input parameters are usually a collection of initial topography parameters and other input parameters that describe the hydraulic or sedimentological dispersion characteristics of a selected geological area. In some examples, a history of deformation and movement, such as subsidence, may also be used as parameters for the forward depositional simulation to obtain realistic geological results. For some forward numerical models, the spatial and temporal distribution of physical properties and their boundary conditions can also be used as model parameters.

[0037] FIG. 2 shows a table 200 of several example designs of input variables. Each rock type, such as those shown in the example depositional environment 100 of FIG. 1, can be associated with a range for that rock type's growth rate. For example, the lagoon 110 can be associated with a growth rate of 10-80 meters per million years. The bank crest 120 can be associated with a growth rate of 40-110 meters per million years. The algal platform 130 can be associated with a growth rate of 0-70 meters per million years. The deep open marine 140 can be associated with a growth rate of 0-70 meters per million years. First step is doing a set of initial Latin Hypercube Sampling (LHS) designs. The table 200 presents an example of such initial LHS designs.

[0038] FIG. 3 shows three examples of simulated models and a key 301 for interpreting the models.

[0039] With the initial LHS designs available, a set of parameters for forward depositional models can be obtained. The forward depositional modeling can be obtained with a batch process that uses the parameters as inputs. In some implementations, this process can be automatic, thus relieving huge amounts of labor. For example, 10, 20, 50, 100, or more models can be simulated and used for such experiments.

[0040] In FIG. 3, a model 310 represents the facies-stacking pattern for a well (the true observed vertical profile from a well). Model 310 is based on observed data, for example, measurements obtained while drilling a well (a well log). The model shows various layers of bank crest 302, lagoon 303, algal platform 304, and deep ocean marine 305 layers.

[0041] A model 320 represents a stacking pattern of a simulation produced from manual parameter inference (the vertical profile extracted from the simulated model using the proposed method). A model 330 represents a stacking pattern of a simulation result obtained from the processes (the vertical profile extracted from simulated model but the inverse parameters are manually inferred) that will be described in more detail in subsequent paragraphs. A comparison of the three models 310-330 shows that the model 330 more closely resembles the model 310 than does the model 320.

[0042] A kriging surrogate modeling technique is then used to rank and identify relationships (correlations) between the initial collection of LHS designs and the mismatch values calculated from comparisons of models and wells. In some examples, the efficient global search and expected improvement principle implemented in this technique can improve the likelihood that the next suggested design will reduce the uncertainty of the surrogate model built between the LHS design and the mismatch value. Based on a recommended parameter, the process is run forward until the iteration meets various predetermined criteria, such as by determining that the mismatch value is less than a predetermined amount, or by determining that the process has iterated more than a predetermined maximum iteration count. In some implementations, during the surrogate modeling and iteration procedure, if the maximum expected improvement is small enough, then the new mismatch value will be calculated from the surrogate model not the forward modeling simulation. The modeling techniques will now be described in more detail.

[0043] Using the techniques described in this document, any appropriate recognized input parameter for forward depositional modeling (such as initial bathymetry, input sediment composition, rates of fluvial discharge, transport efficiency) can be inferred automatically with a target to reproduce the prior observation data.

[0044] The techniques described in this document provide an automated way to perform calibration of forward depositional models based on available prior observation data (sometimes expressed as well logs). The procedure includes the following general stages:

[0045] (1) Performing conditioning data (for example, previously collected well log data) pre-processing. For example, data previously collected during well path drilling can be projected to forward depositional model grid coordinates. This process will transform the well path into a grid cell index in the simulation model for property extraction from the model, and for mismatch value calculation.

[0046] (2) Constructing an initial experimental design using the Latin Hypercube Sampling design (LHS). The LHS design is transformed to physical values, such as hydraulic, geological, and sedimentological values.

[0047] (3) These initial experimental design runs are performed through a batch mode, which automatically performs the proposed inverse depositional procedure for each of the initial experimental design runs.

[0048] (4) Transforming the original depositional model from the time domain to a stratigraphic-depth domain. In situations in which the outputs of the simulated models are not in an expected order (for example, where the outputs simulated models are saved according to time from oldest to newest instead of newest to oldest), at this stage the models can be transformed into a spatial domain.

[0049] (5) Constructing mismatch value calculations based on the prior observation data and the simulated models. Depending on prior observation data (which could be thickness, facies type, porosity or permeability), different mismatch value calculation approaches can be implemented.

[0050] (6) Building kriging surrogate models based on the input and output of a forward depositional modeling program given a predetermined set of specified input parameters.

[0051] (7) Using a global optimization process to look for a set of input parameters that can maximally reproduce the observed, hard data after using the searched input parameter for forward depositional modeling.

[0052] FIG. 4A is a flow diagram 400 of an example inverse depositional modeling workflow. At 410, an initial LHS design is determined, for example, based on observed well log data.

[0053] At 412, in initial forward simulation is determined. The forward depositional modeling procedure can be considered a numerical experiment in experimental design notation. In some implementations, ignoring the knowledge of the inner functionality of the forward depositional modeling can allow the process to be treated as a black-box model in which only the relation of the input-output variables is considered.

[0054] In many modeling programs, depositional modeling is computationally intensive, therefore a maximum amount of information should be obtained during a limited number of forward simulation runs. To optimize the gain of information from a certain set of runs, these runs are performed according to an appropriate experimental design method.

[0055] Different experimental design methods are often involved in building a surrogate model as a computationally efficient approximation of a computationally expensive numerical experiment. Latin Hyper-cube Sampling (LHS) is used in this example process in order to make representation of the whole range of all input parameters more uniform in each design. In some examples, however, other experimental design approaches can also be used.

[0056] This step is performed to transform the experimental design from uniform space to physical space and to write a set of forward depositional modeling parameter files for later surrogate modeling. For each forward modeling, several recognized parameters are used in the inverse procedure. For example, the parameters can be denoted as:

$$x = \{x_1, x_2, \cdots, x_k\}.$$

[0057] In what follows, the design space or design domain will be referred to as D^k. Different samples from the domain can compose a sampling plan.

[0058] For each parameter x_i in x, there would be a maximum and minimum value for it to draw a sedimentological value to run the forward modeling process. The maximum and minimum values can be denoted as L^i_{max} and L^i_{min}. For example, given the LHS design for parameter x_i is l_i, then, x_i can be calculated as:

$$x_i = (L^i_{max} - L^i_{min})^* \, l_i + L^i_{min} \, .$$

[0059] In some examples, several sets can be run (such as an initial collection of samples). For example, N sets could be run. Given L_{max}^{i} and L_{min}^{i}, the whole parameter design matrix can be obtained:

$$X = \{x^1, x^2, \cdots, x^N\} .$$

[0060] Based on a forward depositional modeling parameter template, a full set of parameter files can be generated based on the process described in this text. A forward modeling program can performed *N* times automatically using a batch script and the template. In the latter iteration(s), the identified parameter set from the optimization procedure is used to construct a parameter file and run the forward stratigraphic modeling process.

[0061] After the forward depositional model is constructed, it is compared with the prior observation data. In some examples, the forward depositional model and the prior observation data may not be in same data or coordinate format. In such examples, some pre-processing or decoding work on simulated runs can be done before doing comparison or mismatch operations. For example, different forward engines and different pre-processing modules may be used to deal with different model output formats.

[0062] In some examples of forward depositional programs, the extraction from the simulated model may not follow the true well trajectory with sufficient precision. As a solution, stratigraphic correlation is performed before well trajectories are compared, which provides a basis for property extraction along the true trajectory of the well path. A chronostratigraphic correlation is performed based on the formation marker of the well log data and the mean thickness of the model. This correlation process will project the well path to the same chronostratigraphic correlation as the simulated depositional model. The index of each cell can be searched and indexed given the well trajectory and the grid definition of the depositional model in spatial depth domain. Then, the properties along the trajectory are obtained from the simulation depositional model for use with later mismatch value calculations.

[0063] At 414, an initial mismatch result is determined. For example, the initial forward simulation can be compared to observed well log data to determine a measurement of how accurately (or not) the initial forward simulation emulates the observed data. The mismatch value guides the surrogate model building and optimization. In some examples, a challenge for well log based calibration is related to the type and nature of the data to be calibrated. As will be discussed in more detail in later paragraphs, in these examples three types of mismatch value calculation approaches are described. They are for interval data such as formation thickness, continuous variable such as permeability and porosity and categorical variables such as lithofacies types or rock types. Those are three common and frequently used observation data types obtained from well log data.

[0064] At 416, stop criteria are received. For example, an iteration limit value can be obtained that represents the maximum number of iterations that the modeling process is allowed to perform, after which the best available model may be identified and provided as the final output of the process 400. In another example, a time limit can be obtained that represents the maximum amount of time that the modeling process is allowed to run, after which the best available model may be identified and provided as the final output of the process 400. In yet another example, a model mismatch threshold may be received that represents a mismatch value for a simulated model that would be considered sufficiently emulative of the observed data.

[0065] At 420, a surrogate model is determined. The surrogate model is an approximation that emulates the relation between the difference of forward simulation and the observed data. The surrogate model is generally simpler and therefore less computationally intensive to run than the more fully featured forward simulation. In the reversion, there is only one surrogate model will be built. This surrogate model is updated after the initial set of (x,y). FIG. 4B shows example conceptual models of example stratigraphic realizations. FIG. 4C shows an example conceptual mathematical representation of a surrogate model.

[0066] After forward model is run, the simulated forward model output is compared with the prior observation hard data. This comparison provides a suggestion of how these models compare to the prior observation data, which are used as constraints. In some implementations, the comparison data can be called the response of experimental, *y*, which is a quantitative measure of a difference between the model and the measured data.

[0067] Assuming the availability of a well log of porosity along certain locations vertically in the study area, the well log data is denoted as S^{obs}. A simulated well log of porosity can be obtained from the same location, denoted as S^{sim}, then the difference between the well logs can be defined as a response variable of the stratigraphic model:

$$y = diff(S^{obs} - S^{sim}) .$$

[0068] The surrogate solution implements construction of a computationally cheap-to-evaluate "surrogate" model *f(x)* that emulates the computationally expensive response of forward stratigraphic model procedure *f(x)*. Here *f(x) is* defined by a k-vector of design variables x $\in$ *D*. In what follows, *D* represents the design space or design domain. Different samples from the domain will compose a sampling plan $X = \{x^{(1)}, x^{(2)}, \cdots, x^{(n)}\}$.

[0069] Based on the available of forward stratigraphic modeling program, we can gain into *f(x)* by some observations or samples $\{x^{(i)} \to y^{(i)} = f(x^{(i)}), i = 1, 2, \cdots, n\}$. These are computationally expensive to obtain and therefore are used sparingly. The task of surrogate modeling is to use this sparse set of samples to construct an approximation *f(x)*, which can be used to make a computationally inexpensive performance prediction for a design x $\in$ *D*.

[0070] With an identified design variable *k*, the learning data set $\{(x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \ldots, (x^{(n)}, y^{(n)})\}$ can be determined. Using a generic structure *f*(x, w), the shape of the model being determined by the set of parameters w. An early step in this process is the selection of the vector w such that the model will fit the hard data. At 422, a minimum mismatch among the surrogate models is identified. Assuming that the surrogate model (expressed as the surface in FIG. 4D) has been built. From the fitted surface/surrogate model, minimum searching can be performed. If the searched minimum value is greater than a predetermined stop minimum criterion, then this surrogate model (the surface) can be identified as being not good enough, and another LHS design and respective *y* variable should be added. The smallest mismatch value will be compared with a predefined stop criteria to decide for a subsequent stop action, such as that illustrated at 430.

[0071] For example, after the forward depositional model runs a simulation, the obtained stratigraphic model can be compared to the prior observed data. This comparison can provide an indication of how these models are different in comparison to the prior observed data that are used as constraints. This will be the response of experiments, denoted as y_i, which is a quantitative measure of the difference between a simulated model and the observed data.

[0072] Based on a prior observation of well log data along certain location vertically in the study area, the well log data is denoted as S_{obs}. A simulated well log, based on the same location, is denote them as S_{sim}, and the simulated depositional model is *N* in total. Then, all the mismatch values would be calculated as:

$$y^i = diff(\boldsymbol{S}_{obs}, \boldsymbol{S}_{sim}), \;\; i = 1, 2, \cdots, N.$$

[0073] Where y^i is the difference between each of simulated models and the current prior observation data set, which would be some thickness, or lithofacies record, or some porosity or permeability sequences. The operator $diff$ is a difference operator. In some implementations, however, the operator might be differently defined depending on the nature of observation data.

[0074] At 430, a determination is made. If the mismatch does not satisfy the stop criteria, then another determination is made at 440. If the amount of time or the number of iterations exceed the thresholds for the maximum number of iterations or the maximum amount of time for performing iterations, then the process 400 continues at 442. For example, the process 400 may be configured to stop after 1000 iterations, or after 10 minutes of computations.

[0075] At 442, a new surrogate model design is obtained. If at 450, the new model's improvement over the previous model is small enough, then at 452 a new mismatch value is calculated. If at 450, the new model's improvement is not small enough, then at 454 forward modeling is performed again. In either case, the LHS design and mismatch result are updated at 465, and a new batch of surrogate models are built based on this information at 420.

[0076] If, however, either of the determinations at 430 or 440 are positive (for example, it is time to stop), then at 460 a file is generated. For example, the best surrogate model found during the previous steps can be saved to a storage medium such as an electronic document that can be saved, archived, and transported.

[0077] At 462, forward modeling is performed based on the saved file. For example, the stored model can be transported on a flash drive to another computer that is used for forward modeling, and that computer can read the flash drive as part of a process of forward modeling.

[0078] FIG. 5 is a flow diagram of an example Latin Hypercube sampling and physical transformation process 500. In some implementations, the process 500 can be the step 410 of the example process 400 shown in FIG. 4A.

[0079] At 510, an experimental variable total number is received. Here, the experimental variable total number is the identified key parameter numbers from a modeler. For example, the total number is four for FIG. 1.

[0080] At 515, an LHS design total number is obtained. Here the total number is the initial LHS design number. For example, in the example of FIG. 2, the total LHS design number is 100.

[0081] At 525, the LHS design is performed. The results from the LHS design is in range of zero to one, or [0,1]. The result is a matrix. The matrix dimension is determined from 510 and 515. For example, in the example of FIG. 2, the dimension is 4x100.

[0082] At 530, the range of each target inverse variable is obtained. For example, the grow rate for each sedimentary type can be obtained. At 535, given the range of each geological parameter and the LHS design in [0, 1] space, the LHS design in geological space is obtained.

[0083] Initial forward depositional modeling results from step 530 are saved in terms of geological time coordinates. For example, along the vertical direction, time increments are equal, and all the simulated properties such as thickness, facies type, or other continuous properties are saved inside this timeframe.

[0084] At 540, a forward model parameter file template is obtained. In some implementations, here the forward modeling program can be run from a parameter file or a template. In some implementations, there can be many variables for a forward modeling to be run. Some of them can be given different values to get different models.

[0085] At 545, a collection of designed keywords is identified from the template. The identified inverse target forward modeling parameter variables are tagged in the template. The tagged variables identify the variables to be replaced by the LHS design in parameter range space as illustrated in FIG. 5.

[0086] At 550, an initial forward modeling parameter file set is generated. In this set, each parameter file is obtained from a LHS design and can be enough to perform a normal forward run.

[0087] FIG. 6A is a flow diagram of an example spatial depth transformation process 600. In some implementations, the process 600 may be performed based on the output of the example process 500 of FIG. 5. In some examples, the time-to-spatial depth transformation can be done before extracting the simulated data values and compared with well log data, which is usually expressed in terms of depth.

[0088] At 610, a stratigraphic model, expressed in terms of geological time coordinates, is received. For example, the output of the example process 500 of FIG. 5 can be received.

[0089] At 620, information about the depths and thicknesses of geological layers can be extracted from the received model. In some implementations, from forward modeling, this information can be saved as a part of the final model but not in explicit format. In order to do spatial transformation, some decoding and extraction works are required to pick those information from the saved forward model which are varies from one forward to another forward modeling program.

[0090] At 630, the stratigraphic model is transformed into spatial depth coordinates. For example, the model may be analyzed to determine that the model describes a lagoon layer that is 10 meters think, a bank crest layer that is 100 meters thick, an algal platform that is 150 meters thick, and a deep open marine layer that is 90 meters thick.

[0091] At 640, the spatial correlation in spatial depth coordinates is provided. After transforming the model from time to spatial space, at 650 the simulated properties of some pseudo-wells are extracted. The top depths of the wells, however, might not all have the same depth. At 660, a spatial stratigraphic correlation in spatial depth coordinates is performed for the extracted pseudo-wells. The spatial correlation causes the tops for all the wells to start from same depth. This correlation also causes a correct mismatch calculation from each property for all the wells. In reservoir, the observed wells have their respective spatial locations and respective trajectories. Such location and trajectory information can be projected to the numerical models, an example of which is shown as FIG 6B. FIG. 6B shows example two and three-dimensional projections of example well trajectories.

[0092] FIG. 7A is a flow diagram of an example mismatch determination processes. After the model is transformed from time domain to spatial depth domain, for example as in the process 600 of FIG. 6A, a transformed stratigraphic correlation is applied to the simulation domain, which will ensure the model is saved in a simulated domain that is divided into small cells, and those cells (3D cubic cells) are the same size. FIG. 7B shows a graphical example of a time to spatial transformation of a model. FIG. 7C shows an example grid values in a spatial transformation of a model.

[0093] FIGs. 7B and 7C show small examples to illustrate the process of time to spatial transformation in a model and in a well. Subfigures 750a and 760a show examples of simulated outputs from a traditional forward depositional model. The properties as recorded according simulation time increment along vertical direction. Subfigures 750b and 760b show examples of transformations of the simulated model from time record to spatial coordinates. The top or bottom might not occur at same spatial depth. Subfigures 750c and 760c show examples of stratigraphic correlation transformations. The model properties are saved in each cell.

[0094] In some implementations, depending on different forward engines used, different output data saving logic can be adopted, but the same general principle can be implemented. That is, in order to extract a simulated property from a prior observation location, the coordinate should be same. The proposed methodology here is illustrated with specific output model data. From the forward simulated software, the formations are saved in a chronological order (such as by year) from oldest to newest. Properties, such as thickness of the formation, facies type, and other (including continuous) measurements such as porosity, permeability, sand ratio, and combinations of these or any other appropriate property of the formation are saved in each time layer, which is simulated from substantially equally increased geological time.

[0095] Based on the vertical depth and thickness information of each geological simulation time, the model can be expressed in spatial depth domain. After the model is transformed from time domain to spatial depth domain, a stratigraphic correlation transformed is applied to the simulation domain, which will ensure that the model is saved in a “sugar-block” like conceptual arrangement of grid cells. In some implementations, the intention of this arrangement can be to provide easy and precise hard data extraction for later mismatch function calculations.

[0096] For the stratigraphic correlation transformation, the new relative spatial location is obtained using following equation:

$$Z_{rel} = \frac{Z - Z_{cb}}{Z_{ct} - Z_{cb}} T.$$

Here, Z_{rel} represents the relative spatial depth in space domain, Z_{cb} represents the stratigraphic bottom, Z_{ct} represents the stratigraphic top, T represents the mean thickness between Z_{cb} and Z_{ct}. Converting all depth measurements to Z_{rel} permits modeling each reservoir choronostratigraphic layer in regular Cartesian coordinates and thus to easy comparison between models and wells.

[0097] FIG. 7A is a flow diagram of an example mismatch determination process 700. In some implementations, the process 700 can be performed on the data provided by the example process 600 of FIG. 6A.

[0098] At 710, target formation thicknesses are received. For example, the process 600 can provide a collection of information that describes formation thicknesses, and that information can be received for use at step 710.

[0099] At 720, corresponding thicknesses are identified from simulated models. For example, both the well log data and the simulated data can include a first layer, a second layer, and a third layer (and so on), each having its own thickness.

[00100] At 730, a mismatch is calculated between target and simulated formation thicknesses. For example, the well log data may indicate the presence of layers that are 100, 150, 75, and 120 meters thick, respectively, while a simulated model may describe layers that are 110, 100, 80, and 120 meters thick respectively. In this example, the mathematical differences between the two data sets can be compared to determine the amount of mismatch between the various layers, which in this example would be 10, 50, 5, and 0 meters, respectively.

[00101] Usually, the sequence stratigraphic framework for the target reservoir is established before forward depositional modeling is performed. In this example, it is assumed that the target strata have already been identified by modelers and has already been noted as horizon data.

[00102] Such frameworks, expressed as horizons, which can also be recognized from the simulated model along a vertical direction from clear geological time definition. The process 700 identifies the top and bottom of the target well, denoted here as h_{obs}. Then, at the same well location, from each simulated model, a simulated thickness is calculated from the same top and bottom of same stratigraphy is identified, denoted here as h_{sim}^{i} . The differences between the observation well and each simulated model are represented as:

$$y_{thickness}^{i} = \left|\boldsymbol{S}_{obs} - \boldsymbol{S}_{sim}^{i}\right| = \left|h_{obs} - h_{sim}^{i}\right|,\ i = 1,2,\cdots N.$$

Here, index *i* is the index of the simulated model.

[00103] FIG. 8 is a flow diagram of an example mismatch determination process 800. In some implementations, the process 800 can be performed on the data provided by the example process 600 of FIG. 6A.

[00104] At 810, target facies stacking patterns are received. For example, the process 600 can provide a collection of information that describes how geological layer types are arranged on top of each other, and that information can be received for use at step 810.

[00105] At 820, corresponding stacking patterns are identified from simulated models. For example, both the well log data and the simulated data can include a bank crest layer stacked upon a lagoon layer, stacked upon an algal platform layer, stacked upon a deep ocean marine layer (and so on).

[00106] At 830, a mismatch is calculated between target and simulated formation thicknesses. For example, the well log data may indicate the presence of a bank crest layer stacked upon a lagoon layer, stacked upon an algal platform layer, stacked upon a deep ocean marine layer, while a simulated model may describe a bank crest layer stacked upon an algal platform layer, stacked upon another bank crest layer, stacked upon an algal platform layer, stacked upon a deep ocean marine layer. In this example, the ordering differences between the two data sets can be compared to determine the amount of mismatch between the various layers. For example, the simulated model may be expressed as mismatching the observed data by 10%, 20%, 1%, or any other appropriately descriptive value.

[00107] For facies stacking patterns, the first step is numerical coding of facies type of the research domain. As an example, the facies in the research domain can be $[domits, sand, shale]$, and these values can be numerically transformed to be represented as [1,2,3]. In some examples, the facies codes can be transformed into an integer set, $[1,2,\cdots,K]$ with aim being to compare them numerically. In the current example, it is assumed that the observation well of the current formation is known, and from top to bottom there will be *n* observations in total. The structure of the formation can be denoted as $\boldsymbol{S_{obs}} = \{k_1, k_2, \cdots, k_n\}$, where each observation k_i is one facies type from the set $[1,2,\cdots,K]$.

[00108] From the simulated model, a simulated facies stacking sequence can also be extracted from the same well location from each simulated stratigraphic model, which is denoted as S_{sim}^i. In many examples, the facies observation numbers from the simulated model are different from numbers obtained from the prior observed well data. Assuming that the observation facies number is *m*, the structure of the simulated formation can be represented as:

$$\boldsymbol{S_{sim}^i} = \{k_1^i, k_2^i, \cdots, k_m^i\}.$$

[00109] Each simulated well is then re-sampled. For example, the maximum facies observation number can be implemented whenever it is equal to *m* or *n*. The facies observation sequence can re-sampled according the maximum number of *m* or *n*. After the sequence is re-sampled, they are in same observation length. An indicator transformation is performed upon the layers:

$$I_j^i = \begin{cases} 1 & if\ k_j \neq k_j^i \\ 0 & otherwise \end{cases},\ j = 1,2,\cdots,n;\ \ i = 1,2,\cdots,N.$$

[00110] Here index i would be the simulated model, and index j would be the facies type found along a selected trajectory in the model. Then, the response variable y_i from the sequence pairs (S_{sim}^i, S_{obs}) is calculated as:

$$y_{cat}^i = \left| \boldsymbol{S_{obs}} - \boldsymbol{S_{sim}^i} \right| = \frac{1}{n}\sum_{j=1}^{n} I_j^i.$$

[00111] FIG. 9 is a flow diagram of an example mismatch determination process 900. In some implementations, the process 900 can be performed on the data provided by the example process 600 of FIG. 6A.

[00112] At 910, target (continuous) well logs are received. For example, the process 600 can provide a collection of information that describes sensor data detected at various points along the length of a wellbore (which may be serpentine rather than perfectly linear or vertical), and that information can be received for use at step 910.

[00113] At 920, corresponding simulated well logs are identified from simulated models. For example, the path of the actual well can be recreated in the simulated models, and simulated logs of the simulated well bore can be obtained.

[00114] At 930, a mismatch is calculated between target and simulated well logs. For example, the well log data may indicate the presence of bank crest for the first 100 meters, lagoon for the next 150 meters, algal platform for the next 50 meters, an another stretch of lagoon for the next 50 meters, while a simulated model may describe the presence of bank crest for the first 105 meters, lagoon for the next 200 meters, and deep ocean marine for the next 50 meters. In this example, the mathematical differences between the two data sets can be compared to determine the amount of mismatch between well logs, which can be expressed as a fractional value, a percentage value, or any other appropriate expression of mismatch between data sets.

[00115] Continuous measurement along the well trajectory usually refers to the measurement of properties such as porosity, permeability, or sand ratio. Assuming the observed continuous property data are:

$$\boldsymbol{S}_{obs} = f_j, where: j = 1, 2, \cdots, n.$$

[00116] From one of the simulated models, the simulated measurement can be determined for same well trajectory and denoted as:

$$\boldsymbol{S}_{sim}^{i} = g_j^i, \quad where:\ j = 1, 2, \cdots, n; i = 1, 2, \cdots, N.$$

[00117] In some examples, the simulated wells at the observation location might be different. In such examples, a resampling can be done to a simulated pseudo-well extracted from each simulated well. The whole sequence can re-sampled according the number *n*, and a final mismatch value y_{cont}^i from the continuous measurements would be calculated as:

$$y_{cont}^i = \left| \boldsymbol{S}_{obs} - \boldsymbol{S}_{sim}^{i} \right| = \frac{1}{n}\sum_{j=1}^{n} |g_j - g_j^i|.$$

The index *i* represents the simulated model, and index *j* represents the measured property along the selected trajectory in each of the simulated models.

[00118] In some examples of the inversion procedure, a sequence calibration procedure can be adopted. For example, a certain stratigraphic formation thickness could be fitted first. After that, the categorical variables (such as facies or rock type) can be fitted, and then continuous measurements (such as porosity and permeability) can be fitted. In another example, the user can define a global objective function for calibration at one time. In this case, a global mismatch value could be given as $y_{glob}^i = \lambda_{thickness} \cdot y_{thickness}^i + \lambda_{cat} \cdot y_{cat}^i + \lambda_{cont} \cdot y_{cont}^i$, where $\lambda_{thickness}$, λ_{cat}, and λ_{cont} are weights for each component of mismatch calculated from thickness, categorical and continuous variable.

[00119] FIG. 10 is a flow diagram of an example parameter set generation process 1000. At 1010, a current surrogate model is received. For example, the process 1000 can be used in a generally iterative process in which a number of surrogate models are produced and refined, and at 1010 one of the surrogate models produced in the current iteration can be received. In some implementations, the surrogate model received at 1010 can be the output of any one of the example processes 700, 800, or 900 of FIGs. 7A, 8, and 9.

[00120] At 1020, a determination is made as to whether or not the process 1000 is on its final iteration. If it is, then at 1030 a mismatch function is performed to associate a mismatch score from the surrogate model, which also surface that is fitted based on the inverse target variables. According to the minimum mismatch value, a LHS design can be solved and will be the optimal of the inverse procedure and will be used for the procedure in 1050.

[00121] At 1032, the LHS design having the relatively least degree of mismatch is identified based on the mismatch scores. This is the core technique from the optimization. The surrogate model will connect the input parameter and the mismatch value calculated from comparison of prior observation well log and the simulated model. Thus, it will surrogate the function of complex forward deposition simulation engine and save computing when searching for optimal input parameters for a best calibration of prior hard data. In some examples, prior data from the deposition model can be collected through seismic surveys, well logs, and others processes. In the examples described in this document, the focus has been on the calibration of well log data. However, in other examples, the inverse general principle is substantially the same, with differences in the calibration of different data is the mismatch value calculation that is used.

[00122] If at 1020 it is determined that the process 1000 is not in its final iteration, then the process 1000 continues at 1040. At 1040, the design that provides the relatively greatest amount of improvement to the surrogate model is identified.

Since, in this example, the minimum mismatch value from the surrogate surface is still greater than the stop criteria, further surrogate works are performed. The maximum improvement algorithm will ensure next LHS design will bring maximum improvement to the surrogate model.

[00123] At 1042, from 1040, a best candidate for next LHS design is obtained. This LHS design is in [0,1] space. It will transformed to geological space and will be used to construct one parameter set for procedure 1050.

[00124] At 1050, a parameter set based on the outputs of 1032 or 1042 is determined. For example, the parameter set can be generated for use in a forward stratigraphic modeling process.

Surrogate-based optimization techniques make use of the construction of a computationally inexpensive "surrogate" model $\hat{f}(X)$ that emulates the computationally expensive response of a forward model procedure $f(x)$. Here $f(x)$ is defined by a k-vector of design variables: $= \{x_1, x_2, \cdots, x_k\}$. Different designs x^i from the design domain will compose a numerical experimental sampling plan $X = \{x^1, x^2, \cdots x^N\}$., where N is the total experimental sample number.

[00125] Each design sample x^i from the sample design domain will be a set of input forward depositional model parameters and will get one simulated stratigraphic model S^i_{sim} after feeding to a specified forward engine $f(x)$. That is, based on the available of forward depositional modeling program, some simulated models can be obtained and they can be denoted as:

$$\{\boldsymbol{S}^i_{sim} = f(\boldsymbol{x}^i), i = 1,2, \cdots, N\}.$$

[00126] These models are relatively computationally expensive to obtain, and therefore may only be sparingly available. An objective of the surrogate modeling technique is to use this sparse set of designed input/output observation samples to construct an approximation $\hat{f}(X^i)$, which can be used to make a cheap performance prediction for any new design x^*.

[00127] A mismatch value is calculated based on comparing to the prior observation data S_{obs} using the equation: $y^i = diff(\boldsymbol{S}_{obs}, \boldsymbol{S}_{sim}), i = 1, 2, \cdots, N$.

[00128] Then, a pair of input factors and their related responses will compose a set of data as $\{(\boldsymbol{x}^1, y^1), (\boldsymbol{x}^2, y^2), \cdots, (\boldsymbol{x}^N, y^N)\}$, which is used to build the surrogate model $\hat{f}(x)$.

[00129] A generic structure $\hat{f}(X, W)$ is selected, and the shape of the surrogate model is based on the set of parameters W. So, first step in this sub-process is selecting a vector W such that the model will best fit the hard data.

[00130] Kriging prediction are also performed at un-sampled locations. For example, a new design location in the experimental sample domain can be denoted as $\boldsymbol{x}^*$ and the prediction we are going to make is denoted as:

$$\hat{y} = \hat{f}(\boldsymbol{x}^*, \boldsymbol{w}) \text{ at } \boldsymbol{x}^*.$$

[00131] This prediction will be generally consistent with the observed data (initial sampling plan and the calculated observations from the simulated model), and therefore will be generally consistent with the calculated correlation parameters. Hence, a prediction (given our correlation parameters and the prediction) that increases the likelihood that the sample data will be chosen to be used for next surrogate modeling construction iteration.

[00132] An efficient global optimization (EGO) process is designed for the global optimization of computationally expensive-to-evaluate numerical models. The EGO algorithm is adopted to find a representative input parameter set in its super-dimensional space. An initial design (as discussed previously) is determined. Then the algorithms will sequentially visit a current global maximum of expected improvement to the current surrogate model and updates the kriging surrogate model at each iteration.

[00133] In some implementations, the workflow can be performed by evaluating y^i at initial set using the LHS design, estimating a covariance function using the initial design samples, determining the expected improvement for each candidate location in the space, and searching for the maximum expected improvement in design space D^k. The location of the maximum improvement is the next sampled point x^+, which will bring best improvement to the surrogate model. Kriging is then performed for this picked location, and the predication is added to the measured data. A stopping criterion is then identified based on the maximum expected improvement. When the stopping criterion is met, then stop and evaluate the covariance function with the new sample point set, and iterate.

[00134] For the step of evaluating y^i at initial set using the LHS design, it is assumed that the original forward model has been run *N* times using different input parameter sets. A classical space–filling method, such as Latin Hypercube Sampling, could be used. For the step of estimating a covariance function, the kriging-based surrogate modeling is adopted and the training data sets obtained in step previous step will be used, as discussed previously.

[00135] FIG. 11 is a flow diagram of an example process 1100 for calibration of forward depositional models, such as those described in the previous paragraphs.

[00136] At 1110, a forward depositional modelling program is received. In some implementations, the forward depositional modellings can be done through software programs.

[00137] At 1112, a Latin Hypercube Sampling (LHS) design is determined based on the projected forward depositional model input variables.

[00138] At 1114, the LHS design is transformed to a collection of simulated physical values. In some implementations, the collection of simulated physical values can be a collection of at least one of hydraulic values, geological values, and sedimentological values.

[00139] At 1116, a forward modeling process is performed to get all of the forward models.

[00140] At 1118, the forward depositional model is transformed from time domain to stratigraphic-depth domain.

[00141] At 1120, one or more pseudo-wells are determined (extracted) based on the simulated model. In general, the extracted pseudo-wells' locations should be the same as the prior observed or drilled wells in the study area.

[00142] At 1122, a mismatch value is determined based on the transformed forward depositional model and the collection of simulated physical values. In some implementations, determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the first stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values representing differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value.

[00143] At 1124, a kriging surrogate model is determined based on a collection of the LHS designs (which are x variables), the mismatched values (calculated from the comparison of all the simulated forward models and drilled wells which are y values). The surrogate model will connect x and y together with a function.

[00144] At 1126, the surrogate model and the iteration criteria are checked, and at 1130 a determination is made. If the surrogate model is determined to be insufficient, then the process 1100 continues at 1116. If, however, the surrogate model is determined to be good, then at 1140 a minimum mismatch search is performed based on the current surrogate model.

[00145] At 1142, a new LHS design is determined based on the current minimum mismatch search result. For example, a new LHS design can be obtained in order to improve the surrogate model if the surrogate model surface is not good enough. The EGO algorithm can ensure that the next suggested LHS design improves the surrogate model over previously determined models.

[00146] At 1144, a parameter set is generated for forward stratigraphic modeling. For example, when a new LHS design is suggested, that design can provide x for the surrogate model function. The y can be calculated by running the forward depositional model and comparing the simulated output with the observation.

[00147] Implementations of the subject matter and the functional operations described in this specification can be implemented in digital electronic circuitry, in tangibly embodied computer software or firmware, in computer hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. Software implementations of the described subject matter can be implemented as one or more computer programs, that is, one or more modules of computer program instructions encoded on a tangible, non-transitory, computer-readable computer-storage medium for execution by, or to control the operation of, data processing apparatus. Alternatively, or additionally, the program instructions can be encoded in/on an artificially generated propagated signal, for example, a machine-generated electrical, optical, or electromagnetic signal that is generated to encode information for transmission to suitable receiver apparatus for execution by a data processing apparatus. The computer-storage medium can be a machine-readable storage device, a machine-readable storage substrate, a random or serial access memory device, or a combination of computer-storage mediums.

[00148] The terms “data processing apparatus,” “computer,” or “electronic computer device” (or equivalent as understood by one of ordinary skill in the art) refer to data processing hardware and encompass all kinds of apparatus, devices, and machines for processing data, including by way of example, a programmable processor, a computer, or multiple processors or computers. The apparatus can also be, or further include special purpose logic circuitry, for example, a central processing unit (CPU), a field programmable gate array (FPGA), or an application specific integrated circuit (ASIC). In some implementations, the data processing apparatus or special purpose logic circuitry (or a combination of the data processing apparatus or special purpose logic circuitry) may be hardware- or software-based (or a combination of both hardware- and software-based). The apparatus can optionally include code that creates an execution environment for computer programs, for example, code that constitutes processor firmware, a protocol stack, a database management system, an operating system, or a combination of execution environments. The present disclosure contemplates the use of data processing apparatuses with or without conventional operating systems, for example LINUX, UNIX, WINDOWS, MAC OS, ANDROID, or IOS, or any other suitable conventional operating system.

[00149] A computer program may also be referred to or described as a program, software, a software application, a module, a software module, a script, or code can be written in any form of programming language, including compiled or interpreted languages, or declarative or procedural languages. A computer program can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program may, but need not, correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data, for example, one or more scripts stored in a markup language document, in a single file dedicated to the program in question, or in multiple coordinated files, for example, files that store one or more modules, sub programs, or portions of code. A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network. While portions of the programs illustrated in the various figures are shown as individual modules that implement the various features and functionality through various objects, methods, or other processes, the programs may instead include a number of sub-modules, third-party services, components, libraries, and such, as appropriate. Conversely, the features and functionality of various components can be combined into single components, as appropriate. Thresholds used to make computational determinations can be statically, dynamically, or both statically and dynamically determined.

[00150] Described implementations of the subject matter can include one or more features, alone or in combination.

[00151] For example, in a first aspect, a method for geological modeling includes receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transform the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical value, and determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

[00152] Various implementations can include some, all, or none of the following features. The forward depositional model can be based on well log data descriptive of a drilled well path through a predetermined geographical area. The method can also include receiving the well log data descriptive of the drilled well path through the predetermined geographical area, and projecting, based on the well log data, the drilled well path to forward depositional model coordinates in the forward depositional model. The collection of simulated physical values can include a collection of at least one of hydraulic values, geological values, and sedimentological values. The method can also include determining a drilling path based on an identified set of predetermined input parameters, and drilling a well based on the determined drilling path. Determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value. Determining the kriging surrogate model can include determining a collection of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters, determining a collection of approximation models that are emulative of the collection of simulated models, ranking the collection of approximation models based on a comparison of each approximation model to the forward depositional model, and identifying, based on the ranking, an approximation model of the collection of approximation models that is emulative of the surrogate model. Determining a collection of simulated models based on the LHS stratigraphic model and a collection of forward depositional model parameters includes determining kriging predictions for locations not included in the forward depositional model.

[00153] In a second aspect, a system for geographical modeling includes a control system having one or more processors, and a non-transitory computer-readable medium storing instructions executable by the one or more processors to perform operations including receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transform the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values, and determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

[00154] Various embodiments can include some, all, or none of the following features. The system can also include determining a drilling path based on an identified set of predetermined input parameters, and drilling a well based on the determined drilling path. Determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value. Determining the kriging surrogate model can include determining a collection of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters, determining a collection of approximation models that are emulative of the collection of simulated models, ranking the collection of approximation models based on a comparison of each approximation model to the forward depositional model, and identifying, based on the ranking, an approximation model of the collection of approximation models that is emulative of the surrogate model. Determining a collection of simulated models based on the LHS stratigraphic model and a collection of forward depositional model parameters includes determining kriging predictions for locations not included in the forward depositional model.

[00155] In a third aspect, a non-transitory computer-readable medium storing instructions executable by a processing device to perform operations includes receiving a forward depositional model, determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model, performing forward depositional modeling, transforming the forward depositional model from time domain to stratigraphic-depth domain, determining one or more pseudo-wells based on the transformed model, determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values, determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

[00156] Various embodiments can include some, all, or none of the following features. The forward depositional model can be based on well log data descriptive of a drilled well path through a predetermined geographical area. The operations can also include receiving the well log data descriptive of the drilled well path through the predetermined geographical area, and projecting, based on the well log data, the drilled well path to forward depositional model coordinates in the forward depositional model. The operations can also include determining a drilling path based on an identified set of predetermined input parameters, and drilling a well based on the determined drilling path. Determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values can also include identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path, determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path, determining a collection of difference values including differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection, and providing the collection of differences as the mismatch value. Determining the kriging surrogate model can include determining a collection of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters, determining a collection of approximation models that are emulative of the collection of simulated models, ranking the collection of approximation models based on a comparison of each approximation model to the forward depositional model, and identifying, based on the ranking, an approximation model of the collection of approximation models that is emulative of the surrogate model. Determining a collection of simulated models based on the LHS stratigraphic model and a collection of forward depositional model parameters can include determining kriging predictions for locations not included in the forward depositional model.

[00157] Implementations of the subject matter and the functional operations described in this specification can be implemented in digital electronic circuitry, in tangibly embodied computer software or firmware, in computer hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. Software implementations of the described subject matter can be implemented as one or more computer programs. Each computer program can include one or more modules of computer program instructions encoded on a tangible, non-transitory, computer-readable computer-storage medium for execution by, or to control the operation of, data processing apparatus. Alternatively, or additionally, the program instructions can be encoded in/on an artificially generated propagated signal. The example, the signal can be a machine-generated electrical, optical, or electromagnetic signal that is generated to encode information for transmission to suitable receiver apparatus for execution by a data processing apparatus. The computer-storage medium can be a machine-readable storage device, a machine-readable storage substrate, a random or serial access memory device, or a combination of computer-storage mediums.

[00158] The terms “data processing apparatus,” “computer,” and “electronic computer device” (or equivalent as understood by one of ordinary skill in the art) refer to data processing hardware. For example, a data processing apparatus can encompass all kinds of apparatus, devices, and machines for processing data, including by way of example, a programmable processor, a computer, or multiple processors or computers. The apparatus can also include special purpose logic circuitry including, for example, a central processing unit (CPU), a field programmable gate array (FPGA), or an application specific integrated circuit (ASIC). In some implementations, the data processing apparatus or special purpose logic circuitry (or a combination of the data processing apparatus or special purpose logic circuitry) can be hardware- or software-based (or a combination of both hardware- and software-based). The apparatus can optionally include code that creates an execution environment for computer programs, for example, code that constitutes processor firmware, a protocol stack, a database management system, an operating system, or a combination of execution environments. The present disclosure contemplates the use of data processing apparatuses with or without conventional operating systems, for example, LINUX, UNIX, WINDOWS, MAC OS, ANDROID, or IOS.

[00159] A computer program, which can also be referred to or described as a program, software, a software application, a module, a software module, a script, or code, can be written in any form of programming language. Programming languages can include, for example, compiled languages, interpreted languages, declarative languages, or procedural languages. Programs can be deployed in any form, including as stand-alone programs, modules, components, subroutines, or units for use in a computing environment. A computer program can, but need not, correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data, for example, one or more scripts stored in a markup language document, in a single file dedicated to the program in question, or in multiple coordinated files storing one or more modules, sub programs, or portions of code. A computer program can be deployed for execution on one computer or on multiple computers that are located, for example, at one site or distributed across multiple sites that are interconnected by a communication network. While portions of the programs illustrated in the various figures may be shown as individual modules that implement the various features and functionality through various objects, methods, or processes, the programs can instead include a number of sub-modules, third-party services, components, and libraries. Conversely, the features and functionality of various components can be combined into single components as appropriate. Thresholds used to make computational determinations can be statically, dynamically, or both statically and dynamically determined.

[00160] The methods, processes, or logic flows described in this specification can be performed by one or more programmable computers executing one or more computer programs to perform functions by operating on input data and generating output. The methods, processes, or logic flows can also be performed by, and apparatus can also be implemented as, special purpose logic circuitry, for example, a CPU, an FPGA, or an ASIC.

[00161] Computers suitable for the execution of a computer program can be based on one or more of general and special purpose microprocessors and other kinds of CPUs. The elements of a computer are a CPU for performing or executing instructions and one or more memory devices for storing instructions and data. Generally, a CPU can receive instructions and data from (and write data to) a memory. A computer can also include, or be operatively coupled to, one or more mass storage devices for storing data. In some implementations, a computer can receive data from, and transfer data to, the mass storage devices including, for example, magnetic, magneto optical disks, or optical disks. Moreover, a computer can be embedded in another device, for example, a mobile telephone, a personal digital assistant (PDA), a mobile audio or video player, a game console, a global positioning system (GPS) receiver, or a portable storage device such as a universal serial bus (USB) flash drive.

[00162] Computer readable media (transitory or non-transitory, as appropriate) suitable for storing computer program instructions and data can include all forms of permanent/non-permanent and volatile/nonvolatile memory, media, and memory devices. Computer readable media can include, for example, semiconductor memory devices such as random access memory (RAM), read only memory (ROM), phase change memory (PRAM), static random access memory (SRAM), dynamic random access memory (DRAM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), and flash memory devices. Computer readable media can also include, for example, magnetic devices such as tape, cartridges, cassettes, and internal/removable disks. Computer readable media can also include magneto optical disks and optical memory devices and technologies including, for example, digital video disc (DVD), CD ROM, DVD+/-R, DVD-RAM, DVD-ROM, HD-DVD, and BLURAY. The memory can store various objects or data, including caches, classes, frameworks, applications, modules, backup data, jobs, web pages, web page templates, data structures, database tables, repositories, and dynamic information.

Types of objects and data stored in memory can include parameters, variables, algorithms, instructions, rules, constraints, and references. Additionally, the memory can include logs, policies, security or access data, and reporting files. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[00163] Implementations of the subject matter described in the present disclosure can be implemented on a computer having a display device for providing interaction with a user, including displaying information to (and receiving input from) the user. Types of display devices can include, for example, a cathode ray tube (CRT), a liquid crystal display (LCD), a light-emitting diode (LED), and a plasma monitor. Display devices can include a keyboard and pointing devices including, for example, a mouse, a trackball, or a trackpad. User input can also be provided to the computer through the use of a touchscreen, such as a tablet computer surface with pressure sensitivity or a multi-touch screen using capacitive or electric sensing. Other kinds of devices can be used to provide for interaction with a user, including to receive user feedback including, for example, sensory feedback, including visual feedback, auditory feedback, or tactile feedback. Input from the user can be received in the form of acoustic, speech, or tactile input. In addition, a computer can interact with a user by sending documents to, and receiving documents from, a device that is used by the user. For example, the computer can send web pages to a web browser on a user’s client device in response to requests received from the web browser.

[00164] The term “graphical user interface,” or “GUI,” can be used in the singular or the plural to describe one or more graphical user interfaces and each of the displays of a particular graphical user interface. Therefore, a GUI can represent any graphical user interface, including, but not limited to, a web browser, a touch screen, or a command line interface (CLI) that processes information and efficiently presents the information results to the user. In general, a GUI can include a plurality of user interface (UI) elements, some or all associated with a web browser, such as interactive fields, pull-down lists, and buttons. These and other UI elements can be related to or represent the functions of the web browser.

[00165] Implementations of the subject matter described in this specification can be implemented in a computing system that includes a back end component, for example, as a data server, or that includes a middleware component, for example, an application server. Moreover, the computing system can include a front-end component, for example, a client computer having one or both of a graphical user interface or a Web browser through which a user can interact with the computer. The components of the system can be interconnected by any form or medium of wireline or wireless digital data communication (or a combination of data communication) in a communication network. Examples of communication networks include a local area network (LAN), a radio access network (RAN), a metropolitan area network (MAN), a wide area network (WAN), Worldwide Interoperability for Microwave Access (WIMAX), a wireless local area network (WLAN) (for example, using 802.11 a/b/g/n or 802.20 or a combination of protocols), all or a portion of the Internet, or any other communication system or systems at one or more locations (or a combination of communication networks). The network can communicate with, for example, Internet Protocol (IP) packets, frame relay frames, asynchronous transfer mode (ATM) cells, voice, video, data, or a combination of communication types between network addresses.

[00166] The computing system can include clients and servers. A client and server can generally be remote from each other and can typically interact through a communication network. The relationship of client and server can arise by virtue of computer programs running on the respective computers and having a client-server relationship.

[00167] Cluster file systems can be any file system type accessible from multiple servers for read and update. Locking or consistency tracking may not be necessary since the locking of exchange file system can be done at application layer.

[00168] While this specification contains many specific implementation details, these should not be construed as limitations on the scope of what may be claimed, but rather as descriptions of features that may be specific to particular implementations. Certain features that are described in this specification in the context of separate implementations can also be implemented, in combination, in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations, separately, or in any suitable sub-combination. Moreover, although previously described features may be described as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can, in some cases, be excised from the combination, and the claimed combination may be directed to a sub-combination or variation of a sub-combination.

[00169] Particular implementations of the subject matter have been described. Other implementations, alterations, and permutations of the described implementations are within the scope of the following claims as will be apparent to those skilled in the art. While operations are depicted in the drawings or claims in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed (some operations may be considered optional), to achieve desirable results. In certain circumstances, multitasking or parallel processing (or a combination of multitasking and parallel processing) may be advantageous and performed as deemed appropriate.

[00170] Moreover, the separation or integration of various system modules and components in the previously described implementations should not be understood as requiring such separation or integration in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

[00171] Accordingly, the previously described example implementations do not define or constrain the present disclosure. Other changes, substitutions, and alterations are also possible without departing from the spirit and scope of the present disclosure.

[00172] Furthermore, any claimed implementation is considered to be applicable to at least a computer-implemented method; a non-transitory, computer-readable medium storing computer-readable instructions to perform the computer-implemented method; and a computer system comprising a computer memory interoperably coupled with a hardware processor configured to perform the computer-implemented method or the instructions stored on the non-transitory, computer-readable medium.

WHAT IS CLAIMED IS:

1. A method for geological modeling comprising:

receiving a forward depositional model;

determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model;

performing forward depositional modeling;

transform the forward depositional model from time domain to stratigraphic-depth domain;

determining one or more pseudo-wells based on the transformed model;

determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values; and

determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

2. The method of claim 1, wherein the forward depositional model is based on well log data descriptive of a drilled well path through a predetermined geographical area.

3. The method of claim 2, further comprising:

receiving the well log data descriptive of the drilled well path through the predetermined geographical area; and

projecting, based on the well log data, the drilled well path to forward depositional model coordinates in the forward depositional model.

4. The method of claim 1, wherein the collection of simulated physical values comprises a collection of at least one of hydraulic values, geological values, and sedimentological values.

5. The method of claim 1, further comprising:

determining a drilling path based on an identified set of predetermined input parameters; and

drilling a well based on the determined drilling path.

6. The method of claim 1, wherein determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values comprises:

identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path;

determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path;

determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection; and

providing the collection of differences as the mismatch value.

7. The method of claim 1, wherein determining the kriging surrogate model comprises:

determining a plurality of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters;

determining a plurality of approximation models that are emulative of the plurality of simulated models;

ranking the plurality of approximation models based on a comparison of each approximation model to the forward depositional model; and

identifying, based on the ranking, an approximation model of the plurality of approximation models that is emulative of the surrogate model.

8. The method of claim 7, wherein determining a plurality of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters comprises determining kriging predictions for locations not included in the forward depositional model.

9. A system for geographical modeling, comprising:

a control system comprising one or more processors; and

a non-transitory computer-readable medium storing instructions executable by the one or more processors to perform operations comprising:

receiving a forward depositional model;

determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model;

performing forward depositional modeling;

transform the forward depositional model from time domain to stratigraphic-depth domain;

determining one or more pseudo-wells based on the transformed model;

determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values; and

determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

10. The system of claim 9, further comprising:

determining a drilling path based on an identified set of predetermined input parameters; and

drilling a well based on the determined drilling path.

11. The system of claim 9, wherein determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values comprises:

identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path;

determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path;

determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection; and

providing the collection of differences as the mismatch value.

12. The system of claim 9, wherein determining the kriging surrogate model comprises:

determining a plurality of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters;

determining a plurality of approximation models that are emulative of the plurality of simulated models;

ranking the plurality of approximation models based on a comparison of each approximation model to the forward depositional model; and

identifying, based on the ranking, an approximation model of the plurality of approximation models that is emulative of the surrogate model.

13. The system of claim 12, wherein determining a plurality of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters comprises determining kriging predictions for locations not included in the forward depositional model.

14. A non-transitory computer-readable medium storing instructions executable by a processing device to perform operations comprising:

receiving a forward depositional model;

determining a Latin Hypercube Sampling (LHS) stratigraphic model based on the projected forward depositional model;

performing forward depositional modeling;

transform the forward depositional model from time domain to stratigraphic-depth domain;

determining one or more pseudo-wells based on the transformed model;

determining a mismatch value based on the transformed forward depositional model and a collection of simulated physical values;

determining a kriging surrogate model based on the LHS stratigraphic model and the mismatch value.

15. The non-transitory computer-readable medium of claim 14, wherein the forward depositional model is based on well log data descriptive of a drilled well path through a predetermined geographical area.

16. The non-transitory computer-readable medium of claim 15, the operations further comprising:

receiving the well log data descriptive of the drilled well path through the predetermined geographical area; and

projecting, based on the well log data, the drilled well path to forward depositional model coordinates in the forward depositional model.

17. The non-transitory computer-readable medium of claim 14, the operations further comprising:

determining a drilling path based on an identified set of predetermined input parameters; and

drilling a well based on the determined drilling path.

18. The non-transitory computer-readable medium of claim 14, wherein determining a mismatch value based on the transformed forward depositional model and the collection of simulated physical values comprises:

identifying a first collection of geological parameter values representative of geological properties measured at predetermined points along a drilled well path; determining a second collection of geological parameter values representative of simulated geological properties of the LHS stratigraphic model at the predetermined points along the drilled well path;

determining a collection of difference values comprising differences between selected geological parameter values of the first collection and corresponding geological parameter values of the second collection; and

providing the collection of differences as the mismatch value.

19. The non-transitory computer-readable medium of claim 14, wherein determining the kriging surrogate model comprises:

determining a plurality of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters;

determining a plurality of approximation models that are emulative of the plurality of simulated models;

ranking the plurality of approximation models based on a comparison of each approximation model to the forward depositional model; and

identifying, based on the ranking, an approximation model of the plurality of approximation models that is emulative of the surrogate model.

20. The non-transitory computer-readable medium of claim 19, wherein determining a plurality of simulated models based on the LHS stratigraphic model and a collection forward depositional model parameters comprises determining kriging predictions for locations not included in the forward depositional model.

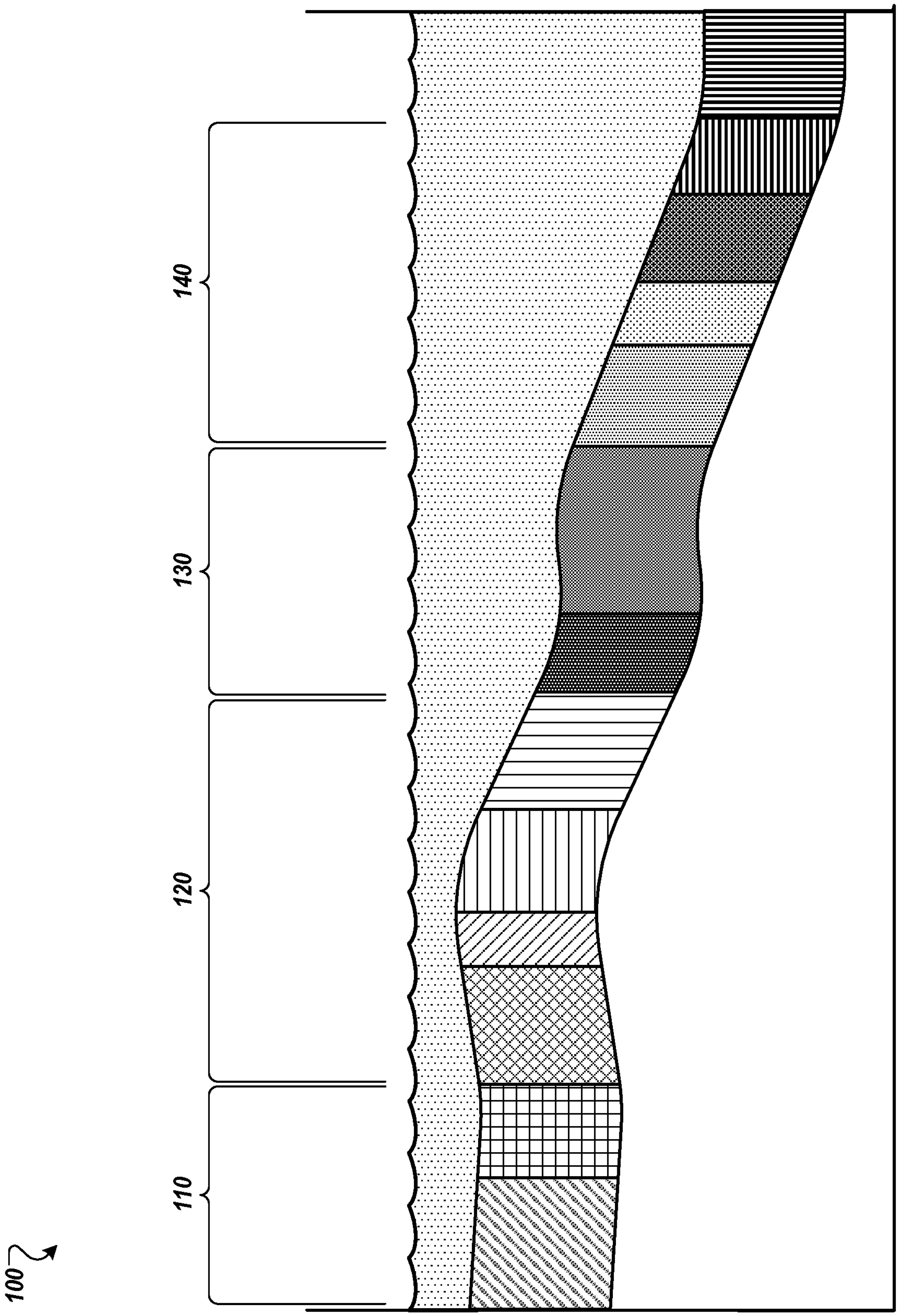

FIG. 1

200

1	1.00000	0.65517	0.00000	0.10345
2	0.96552	0.13793	0.10345	0.89655
3	0.75862	1.00000	0.34483	0.44828
4	0.89655	0.31034	0.17241	0.79310
5	0.10345	0.96552	0.06897	0.96552
	⋮	⋮	⋮	⋮
99	0.03467	0.13034	0.16743	0.01398
100	0.97281	0.19653	0.83175	0.06896

FIG. 2

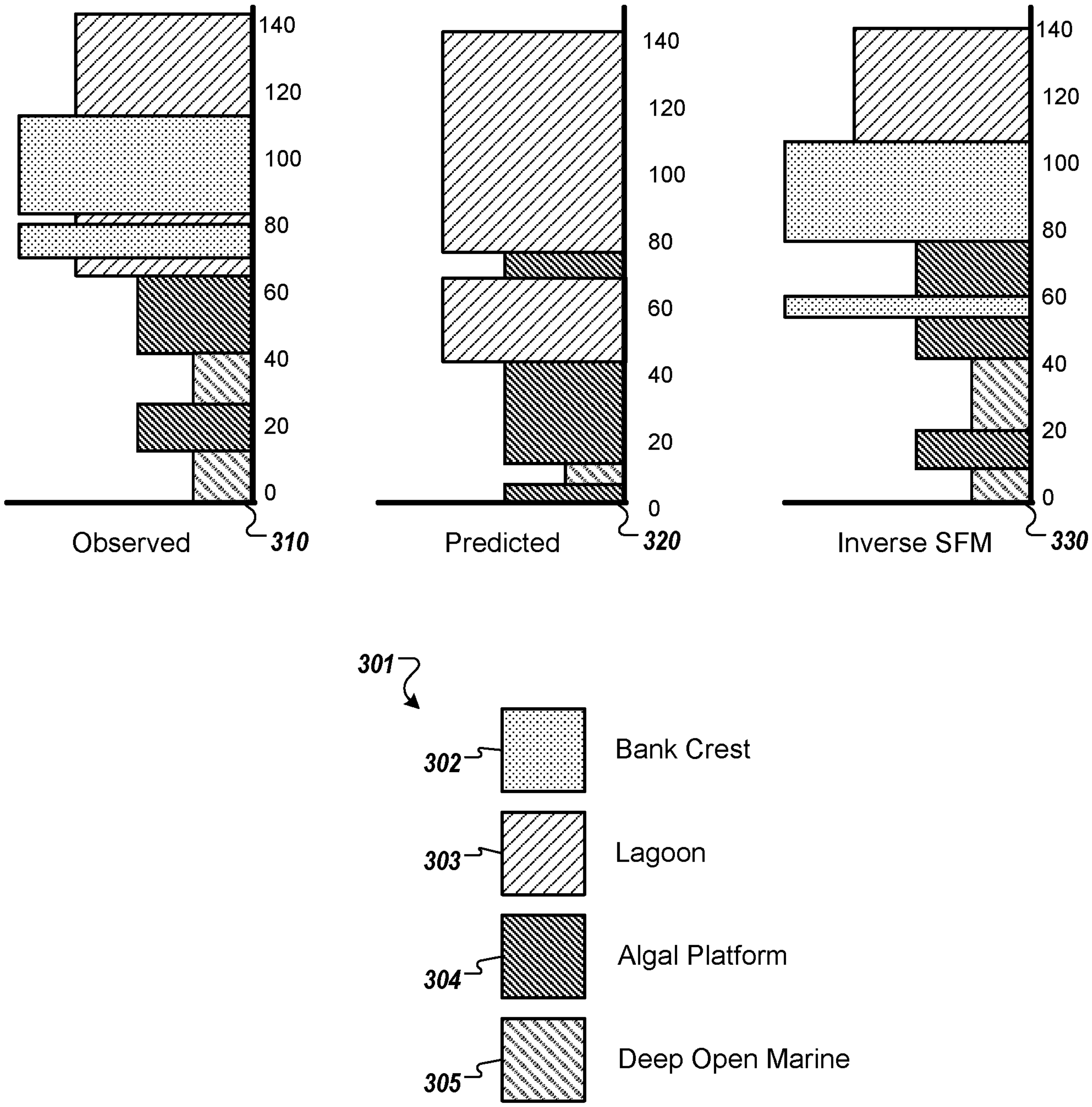
140
120
100
80
60
40
20
0
Observed
310
140
120
100
80
60
40
20
0
Predicted
320
140
120
100
80
60
40
20
0
Inverse SFM
330
301
302
Bank Crest
303
Lagoon
304
Algal Platform
305
Deep Open Marine

FIG. 3

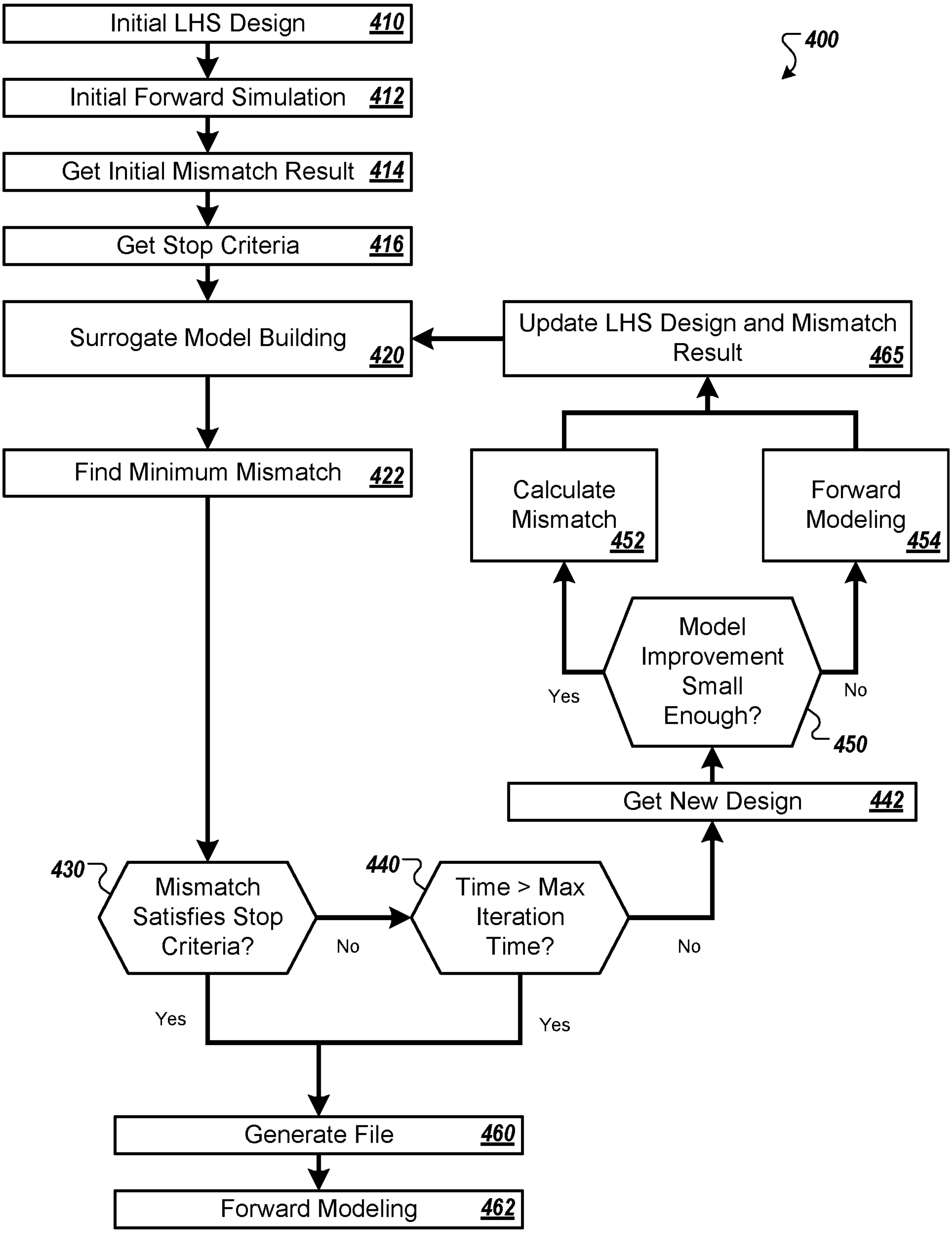
400
Initial LHS Design 410
Initial Forward Simulation 412
Get Initial Mismatch Result 414
Get Stop Criteria 416
Surrogate Model Building 420
Update LHS Design and Mismatch Result 465
Find Minimum Mismatch 422
Calculate Mismatch 452
Forward Modeling 454
Model Improvement Small Enough?
Yes
No
450
Get New Design 442
430
Mismatch Satisfies Stop Criteria?
No
440
Time > Max Iteration Time?
No
Yes
Yes
Generate File 460
Forward Modeling 462

FIG. 4A

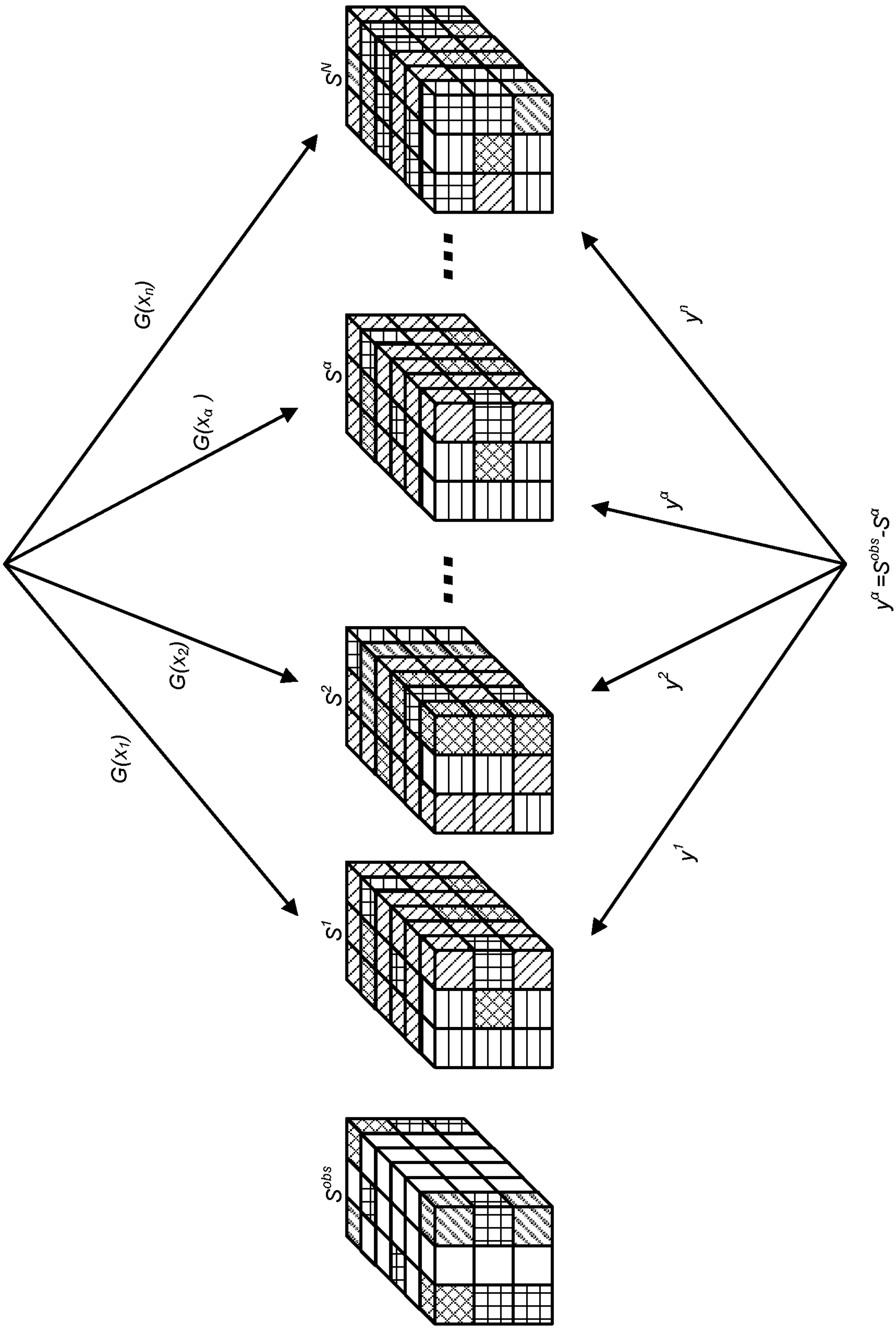

FIG. 4B

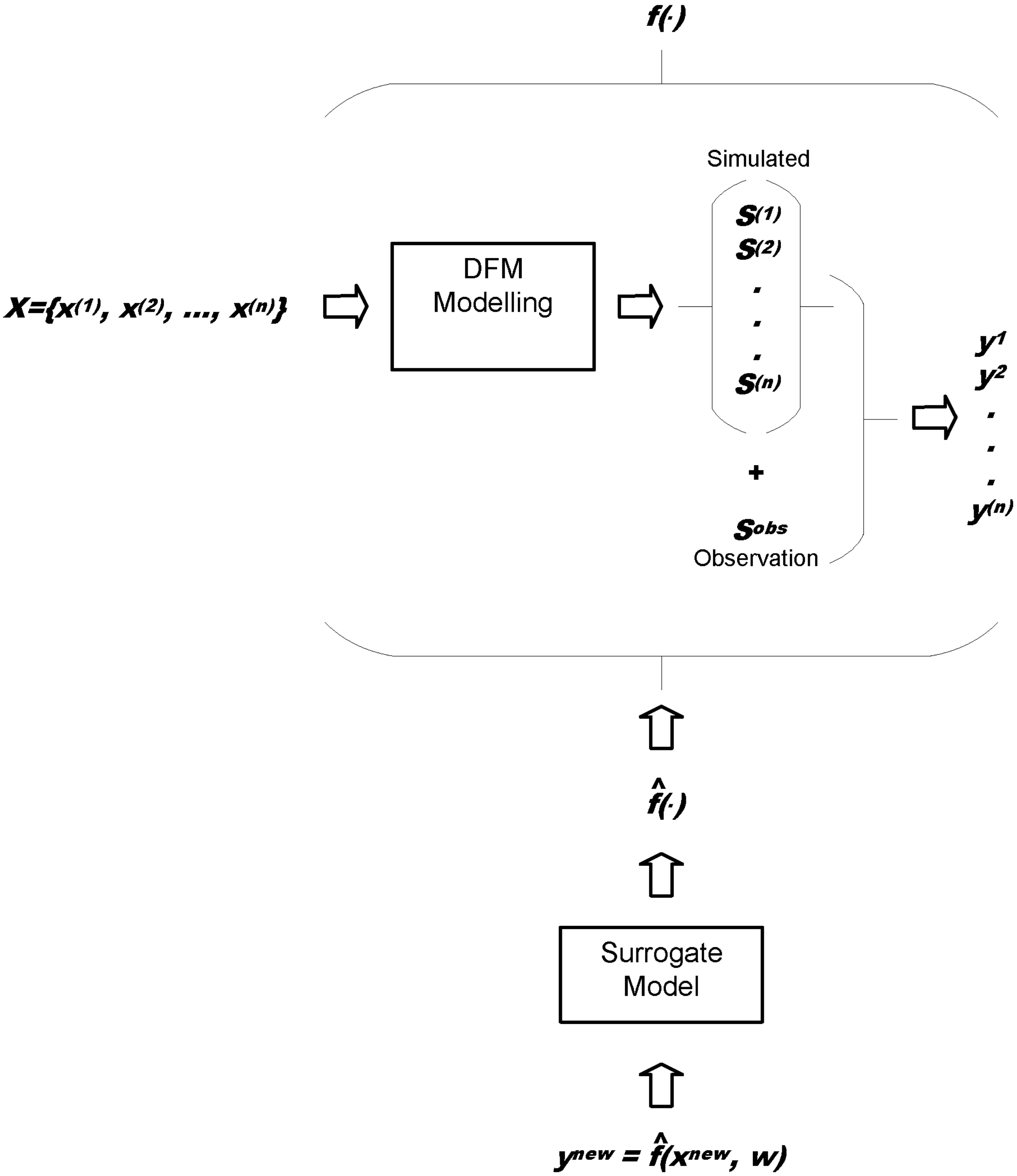
$f(\cdot)$
$X=\{x^{(1)}, x^{(2)}, \ldots, x^{(n)}\}$
DFM Modelling
Simulated
$S^{(1)}$
$S^{(2)}$
.
.
.
$S^{(n)}$
+
S^{obs}
Observation
y^1
y^2
.
.
.
$y^{(n)}$
$\hat{f}(\cdot)$
Surrogate Model
$y^{new} = \hat{f}(x^{new}, w)$

FIG. 4C

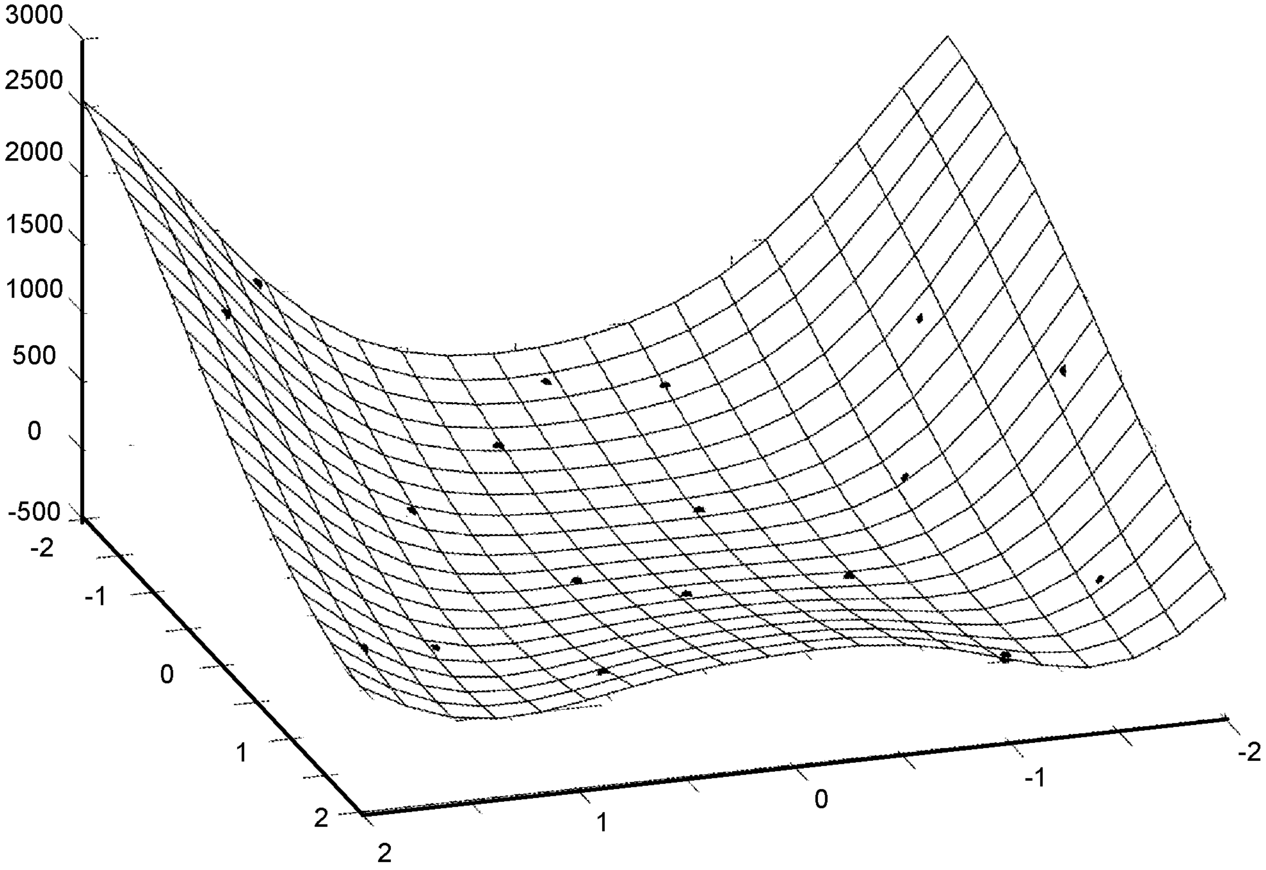

FIG. 4D

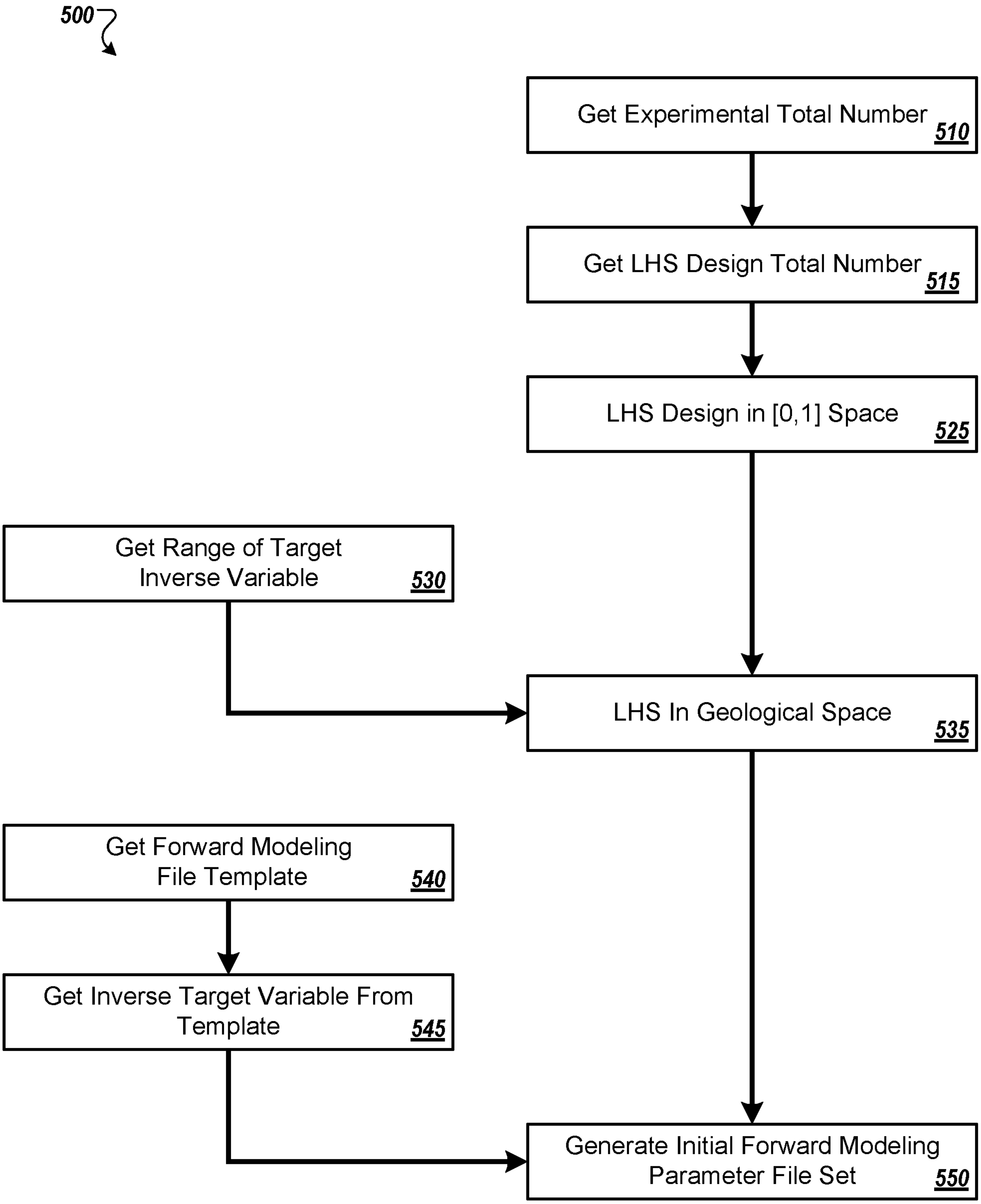
500
Get Experimental Total Number 510
Get LHS Design Total Number 515
LHS Design in [0,1] Space 525
Get Range of Target Inverse Variable 530
LHS In Geological Space 535
Get Forward Modeling File Template 540
Get Inverse Target Variable From Template 545
Generate Initial Forward Modeling Parameter File Set 550

FIG. 5

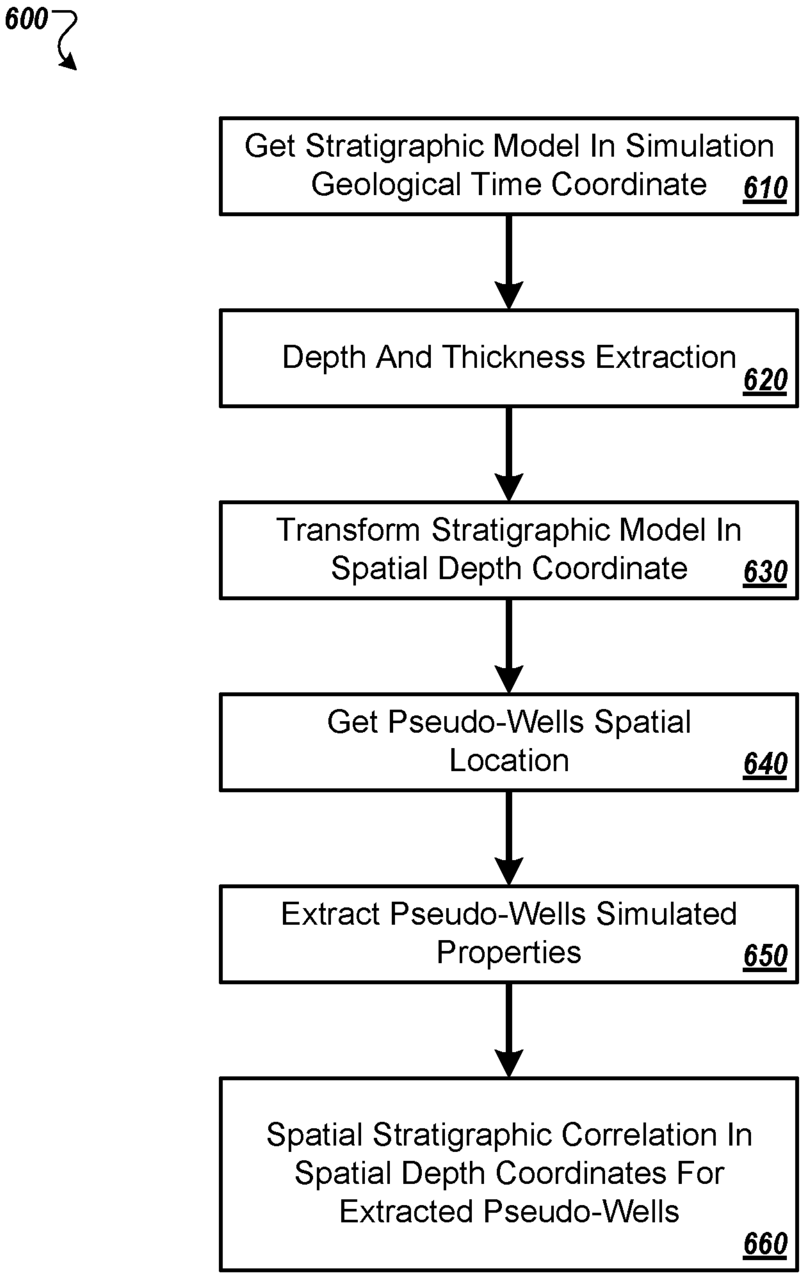
600
Get Stratigraphic Model In Simulation Geological Time Coordinate 610
Depth And Thickness Extraction 620
Transform Stratigraphic Model In Spatial Depth Coordinate 630
Get Pseudo-Wells Spatial Location 640
Extract Pseudo-Wells Simulated Properties 650
Spatial Stratigraphic Correlation In Spatial Depth Coordinates For Extracted Pseudo-Wells 660

FIG. 6A

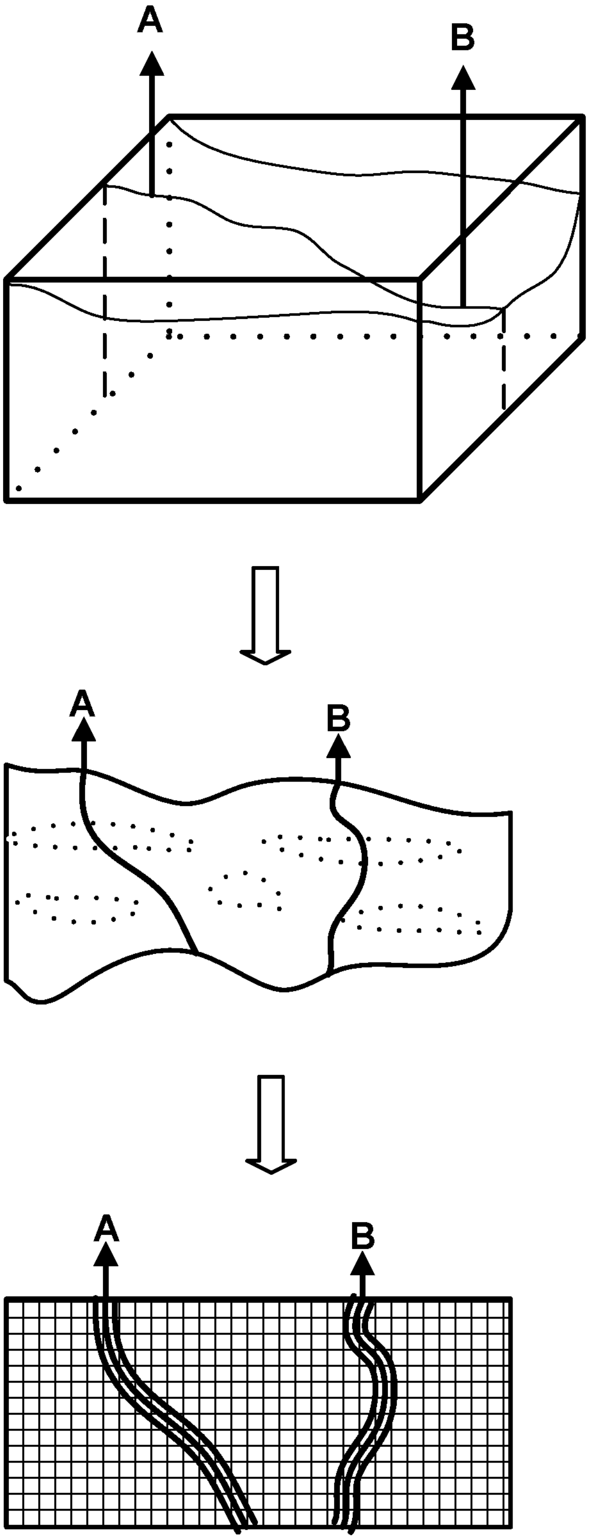

FIG. 6B

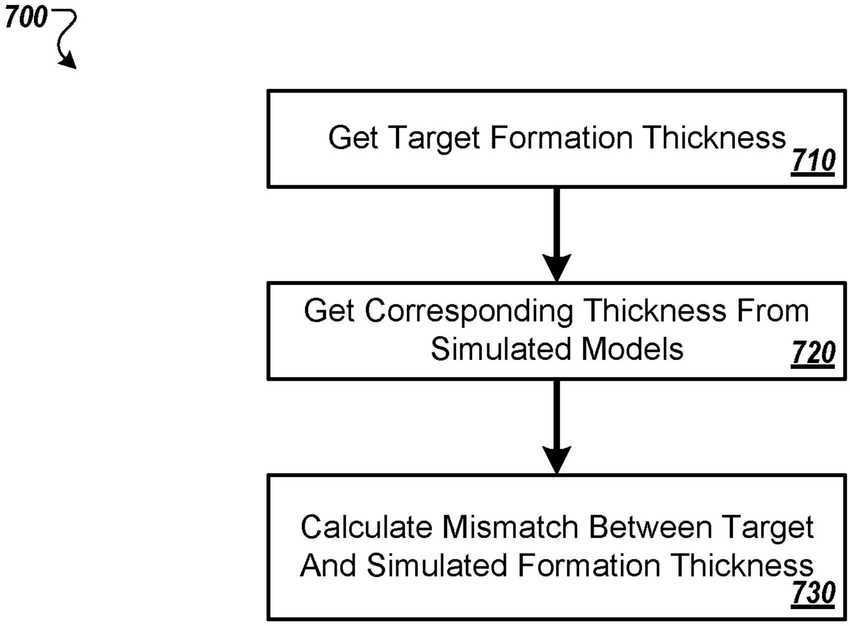
700
Get Target Formation Thickness
710
Get Corresponding Thickness From Simulated Models
720
Calculate Mismatch Between Target And Simulated Formation Thickness
730

FIG. 7A

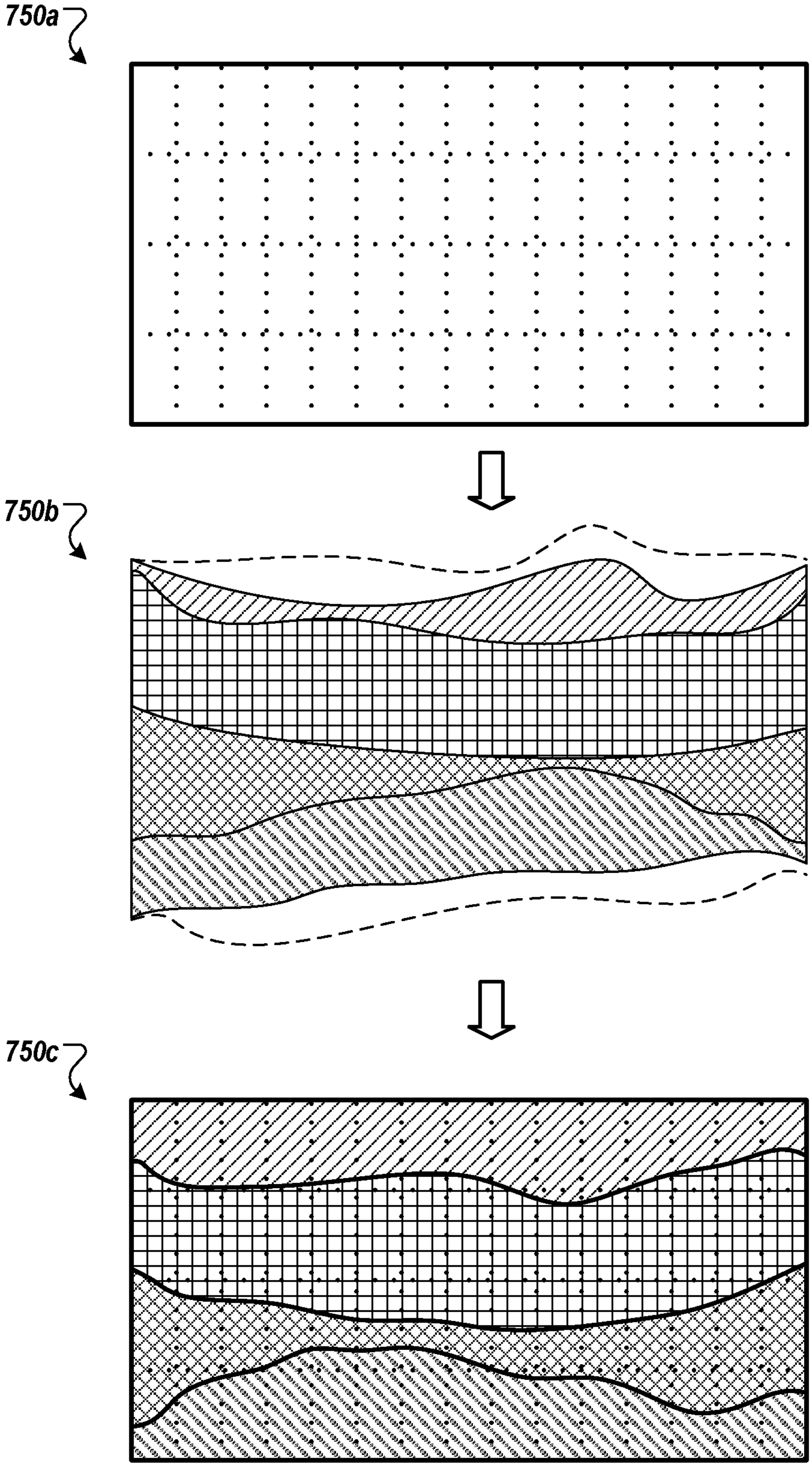

FIG. 7B

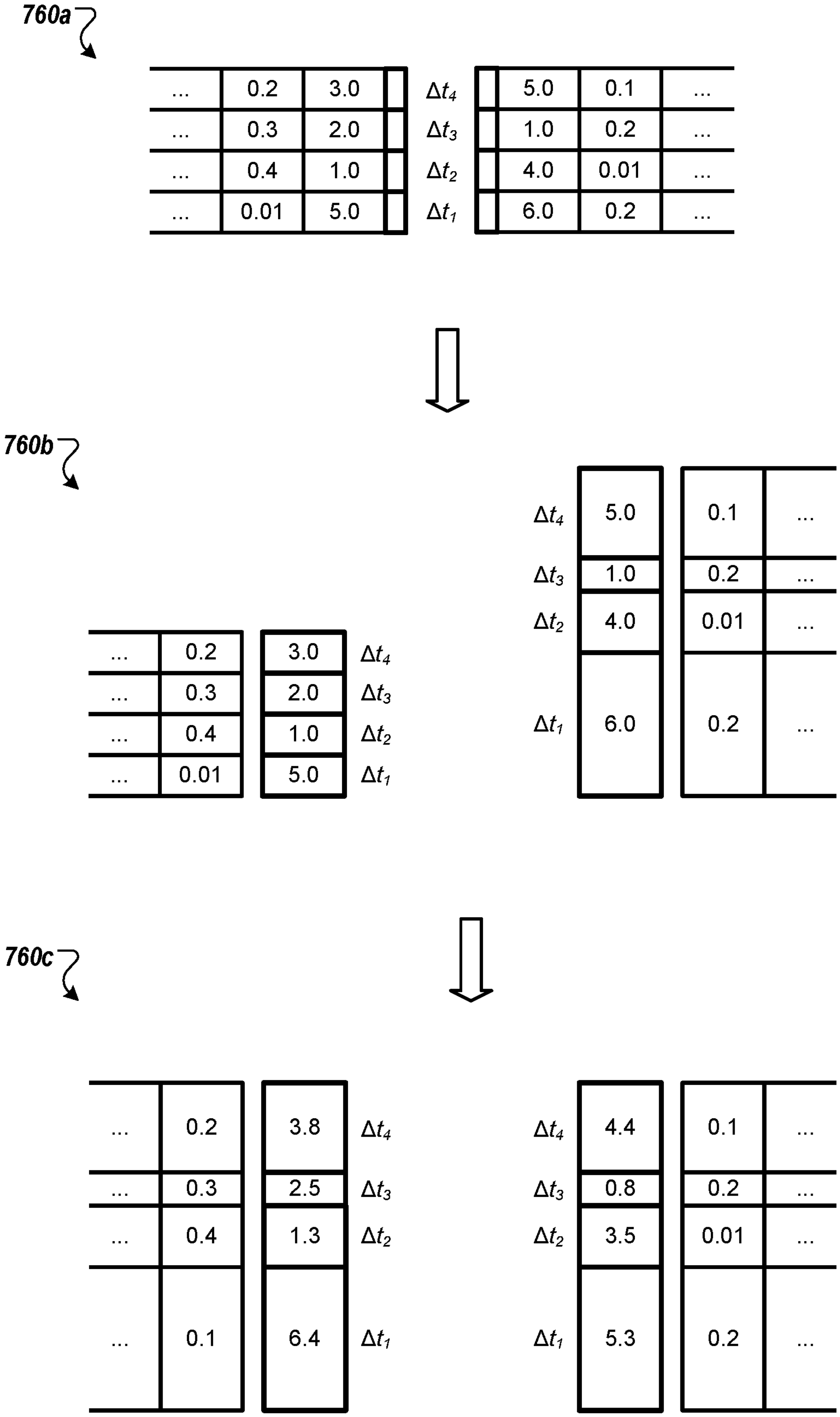
760a
...
0.2
3.0
Δt_4
5.0
0.1
...
...
0.3
2.0
Δt_3
1.0
0.2
...
...
0.4
1.0
Δt_2
4.0
0.01
...
...
0.01
5.0
Δt_1
6.0
0.2
...
760b
Δt_4
5.0
0.1
...
Δt_3
1.0
0.2
...
Δt_2
4.0
0.01
...
Δt_1
6.0
0.2
...
...
0.2
3.0
Δt_4
...
0.3
2.0
Δt_3
...
0.4
1.0
Δt_2
...
0.01
5.0
Δt_1
760c
...
0.2
3.8
Δt_4
4.4
0.1
...
...
0.3
2.5
Δt_3
0.8
0.2
...
...
0.4
1.3
Δt_2
3.5
0.01
...
...
0.1
6.4
Δt_1
5.3
0.2
...

FIG. 7C

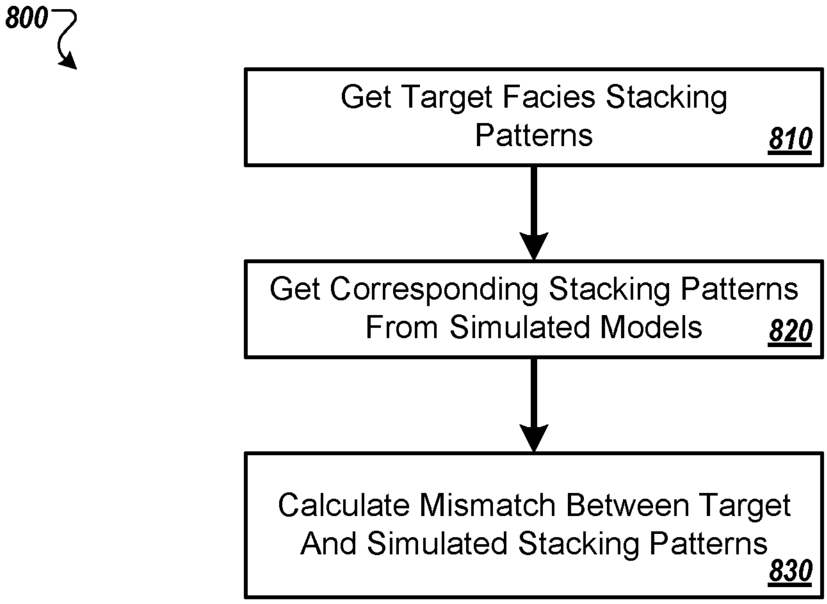
800
Get Target Facies Stacking Patterns
810
Get Corresponding Stacking Patterns From Simulated Models
820
Calculate Mismatch Between Target And Simulated Stacking Patterns
830

FIG. 8

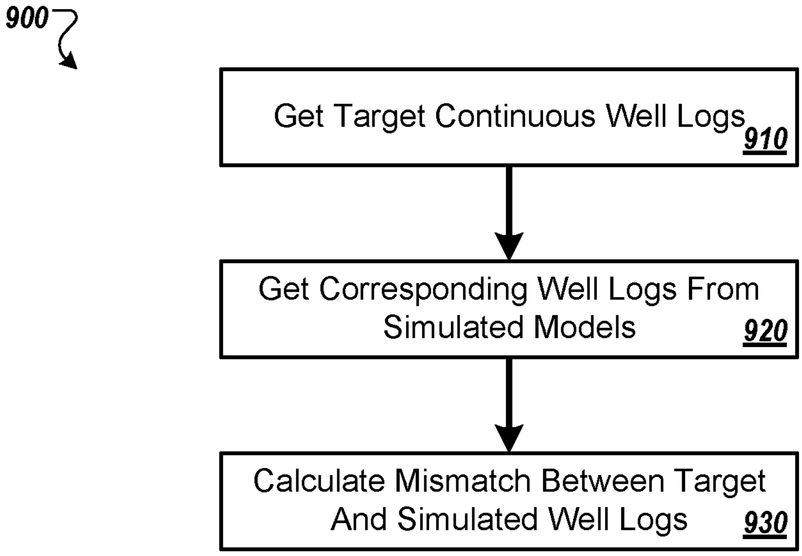
900
Get Target Continuous Well Logs
910
Get Corresponding Well Logs From Simulated Models
920
Calculate Mismatch Between Target And Simulated Well Logs
930

FIG. 9

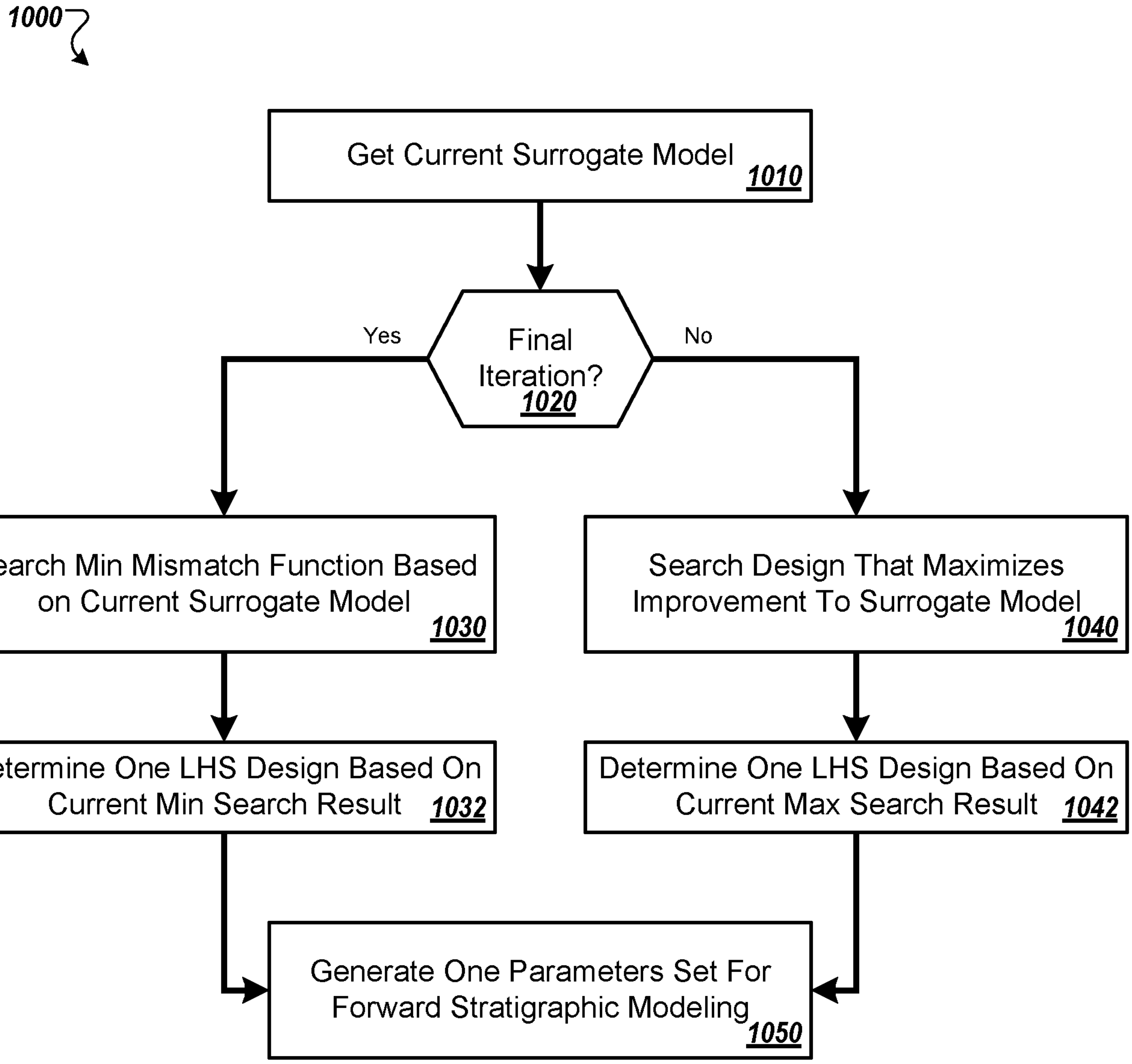
1000
Get Current Surrogate Model 1010
Final Iteration? 1020
Yes
No
Search Min Mismatch Function Based on Current Surrogate Model 1030
Search Design That Maximizes Improvement To Surrogate Model 1040
Determine One LHS Design Based On Current Min Search Result 1032
Determine One LHS Design Based On Current Max Search Result 1042
Generate One Parameters Set For Forward Stratigraphic Modeling 1050

FIG. 10

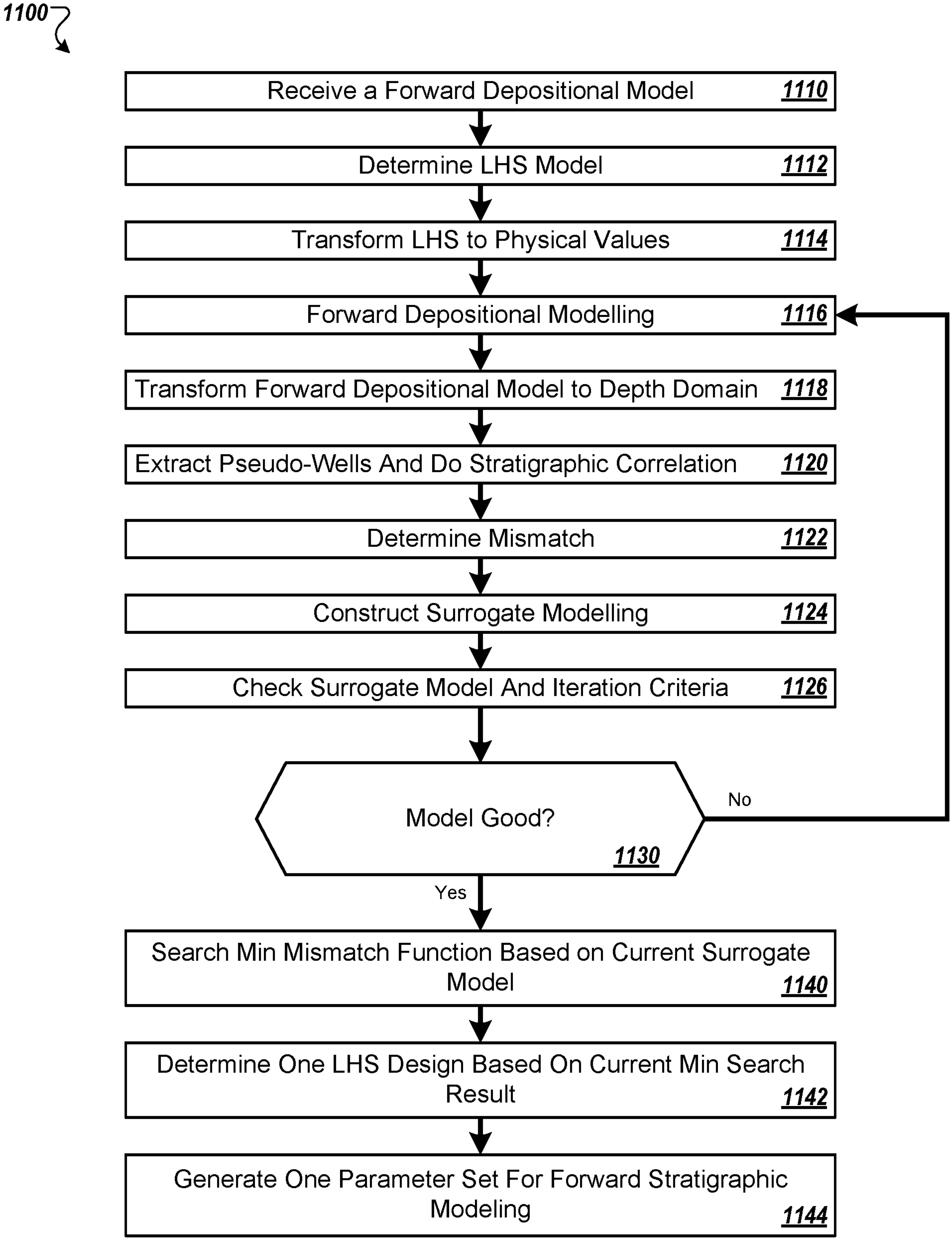
1100
Receive a Forward Depositional Model 1110
Determine LHS Model 1112
Transform LHS to Physical Values 1114
Forward Depositional Modelling 1116
Transform Forward Depositional Model to Depth Domain 1118
Extract Pseudo-Wells And Do Stratigraphic Correlation 1120
Determine Mismatch 1122
Construct Surrogate Modelling 1124
Check Surrogate Model And Iteration Criteria 1126
Model Good? 1130
No
Yes
Search Min Mismatch Function Based on Current Surrogate Model 1140
Determine One LHS Design Based On Current Min Search Result 1142
Generate One Parameter Set For Forward Stratigraphic Modeling 1144

FIG. 11

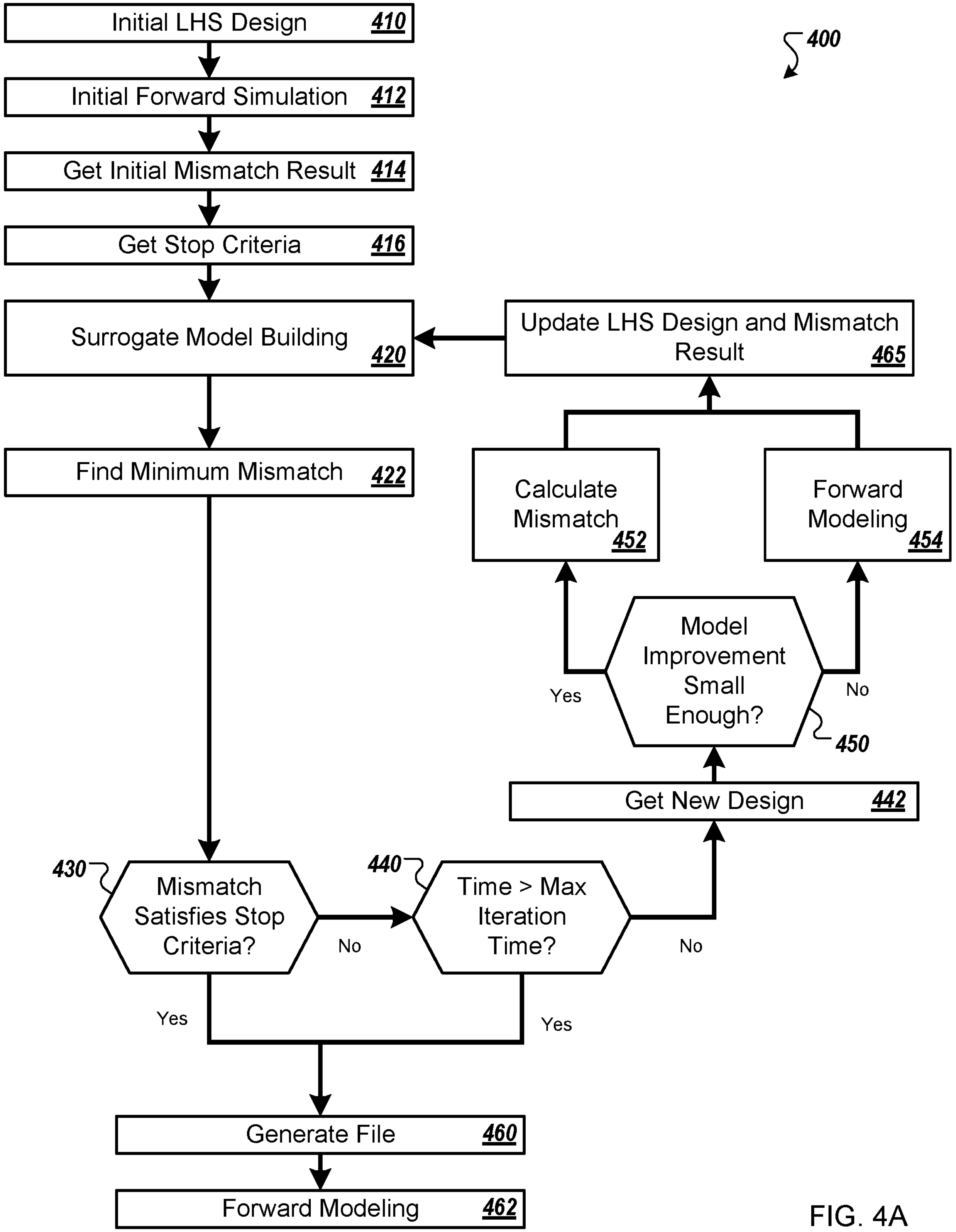
400
Initial LHS Design 410
Initial Forward Simulation 412
Get Initial Mismatch Result 414
Get Stop Criteria 416
Surrogate Model Building 420
Update LHS Design and Mismatch Result 465
Find Minimum Mismatch 422
Calculate Mismatch 452
Forward Modeling 454
Yes
Model Improvement Small Enough?
No
450
Get New Design 442
430
Mismatch Satisfies Stop Criteria?
No
440
Time > Max Iteration Time?
No
Yes
Yes
Generate File 460
Forward Modeling 462

FIG. 4A