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(54) Title: CAPTURING MOST SEVERE FAILURE REGIONS AROUND BOREHOLE IN ANALYTICAL POROELASTIC ANALYSIS

ANALYSIS SETTINGS

WELLBORE STRESS MODEL
TIME-DEPENDENT STRESS (POROELASTIC)

BOREHOLE CONDITION
PERMEABLE

RADIAL RATIO
1.03

☐ WEAK BEDDING PLANE ANALYSIS

☐ WITH BREAKOUT ANGLE
30 DEG

WELLBORE GEOMETRY

TVD
4,724.4 M

BOREHOLE RADIUS
0.0747 M

INCLINATION
0 DEG

AZIMUTH
0 DEG

ELASTIC PROPERTIES

YOUNG'S MODULUS
4.137E+10 PA

POISSON'S RATIO
0.22

IN-SITU STRESSES & PORE PRESSURE

OVERBURDEN STRESS GRADIENT
24.683 KPA/M

MAX HORIZONTAL STRESS GRADIENT
29.407 KPA/M

MIN HORIZONTAL STRESS GRADIENT
18.098 KPA/M

PORE PRESSURE GRADIENT
13.572 KPA/M

MAX HORIZONTAL STRESS AZIMUTH
90 DEG

MUD WEIGHT
70 PCF

FAILURE CRITERIA & STRENGTH PROPERTIES

FAILURE CRITERION
MOHR-COULOMB

SHEAR STRENGTH PARAMETERS
UCS & FRICTION ANGLE

UNIAXIAL COMP STRENGTH (UCS)
88.948 MPA

COHESION
14.28 MPA

FRICTION ANGLE
45 DEG

TENSILE STRENGTH
1.000 MPA

POROELASTIC PROPERTIES

BIOT'S COEFFICIENT
0.8

UNDRAINED POISSON'S RATIO
0.46

PERMEABILITY
0.001 MD

VISCOSITY
1 CP

TIME AFTER WELLBORE DRILLING

TIME INSTANCE #1
15 MIN

TIME INSTANCE #2
2 HR

TIME INSTANCE #3
1 DAY

TIME INSTANCE #4
5 DAY

FIG. 3A

(57) Abstract: A method for performing a borehole operation is disclosed. The method includes determining (201) a characteristic diffusion time that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole, determining (202), based on a pre-determined failure criterion, a critical time of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time, identifying (203) a failure region of the failure occurring at the critical time of the borehole, and performing (204), based on at least the identified failure region, the borehole operation.

HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, 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.

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CAPTURING MOST SEVERE FAILURE REGIONS AROUND BOREHOLE IN ANALYTICAL POROELASTIC ANALYSIS

BACKGROUND

[0001] Stress and pore pressure responses around wellbore are time-dependent, therefore the borehole stability is also time-dependent. The time-dependence can be caused by physical, mechanical, hydraulic, thermal, chemical or rheological mechanisms. For example, fluid diffusion and rock deformation interaction due to hydro-mechanical mechanism plays an important role in wellbore drilling into an unconventional formation.

[0002] Poroelastic analysis is a technique that studies the interaction between fluid flow and solids deformation within a linear porous medium, such as the formation rocks around a wellbore. The deformation of the medium influences the flow of the fluid and vice versa.

SUMMARY

[0003] In general, in one aspect, the invention relates to a method for performing a borehole operation. The method includes determining a characteristic diffusion time that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole, determining, based on a pre-determined failure criterion, a critical time of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time, identifying a failure region of the failure occurring at the critical time of the borehole, and performing, based on at least the identified failure region, the borehole operation.

[0004] In general, in one aspect, the invention relates to a data gathering and analysis system that includes a computer processor, and memory storing instructions, when executed, causing the computer processor to determine a characteristic diffusion time that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole, determine, based on a pre-determined failure criterion, a critical time of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time, identify

a failure region of the failure occurring at the critical time of the borehole, and perform, based at least on the identified failure region, a borehole operation.

[0005] In general, in one aspect, the invention relates to a well system that includes a rig for drilling a borehole, and a data gathering and analysis system comprising functionality for determining a characteristic diffusion time that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole, determining, based on a pre-determined failure criterion, a critical time of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time, identifying a failure region of the failure occurring at the critical time of the borehole, and performing, using the rig and based at least on the identified failure region, a borehole operation.

[0006] Other aspects and advantages will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF DRAWINGS

[0007] Specific embodiments of the disclosed technology will now be described in detail with reference to the accompanying figures. Like elements in the various figures are denoted by like reference numerals for consistency.

[0008] FIGs. 1A and 1B show systems in accordance with one or more embodiments.

[0009] FIG. 2 shows a flowchart in accordance with one or more embodiments.

[0010] FIGs. 3A-3K show an example in accordance with one or more embodiments.

[0011] FIG. 4 shows a computing system in accordance with one or more embodiments.

DETAILED DESCRIPTION

[0012] In the following detailed description of embodiments of the disclosure, numerous specific details are set forth in order to provide a more thorough understanding of the disclosure. However, it will be apparent to one of ordinary skill in the art that the disclosure may be practiced without these specific details. In other

instances, well-known features have not been described in detail to avoid unnecessarily complicating the description.

[0013] Throughout the application, ordinal numbers (e.g., first, second, third, etc.) may be used as an adjective for an element (i.e., any noun in the application). The use of ordinal numbers is not to imply or create any particular ordering of the elements nor to limit any element to being only a single element unless expressly disclosed, such as using the terms "before", "after", "single", and other such terminology. Rather, the use of ordinal numbers is to distinguish between the elements. By way of an example, a first element is distinct from a second element, and the first element may encompass more than one element and succeed (or precede) the second element in an ordering of elements.

[0014] Embodiments of this disclosure provide a method and a system for performing a borehole operation. In one or more embodiments of the invention, a characteristic diffusion time that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole is determined using a poroelastic analysis software. A critical time of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time is then determined based on a pre-determined failure criterion, such as Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-Brown criterion, or Modified Lade criterion. A failure region of the failure occurring at the critical time of the borehole is identified such that the borehole operation is performed based on the identified failure region. In particular, the borehole operation is performed in a manner to mitigate a potential borehole breakout event and prevents a borehole breakout induced problem of spalling, washout, tight hole or stuck pipe.

[0015] FIG. 1A shows a schematic diagram of a well environment in accordance with one or more embodiments. In one or more embodiments, one or more of the modules and/or elements shown in FIG. 1A may be omitted, repeated, and/or substituted. Accordingly, embodiments disclosed herein should not be considered limited to the specific arrangements of modules and/or elements shown in FIG. 1A.

[0016] As shown in FIG. 1A, a well environment (100) includes a subterranean formation ("formation") (104) and a well system (106). The formation (104) may

include a porous or fractured rock formation that resides underground, beneath the earth's surface ("surface") (108). The formation (104) may include different layers of rock having varying characteristics, such as varying degrees of permeability, porosity, capillary pressure, and resistivity. In the case of the well system (106) being a hydrocarbon well, the formation (104) may include a hydrocarbon-bearing reservoir (102). In the case of the well system (106) being operated as a production well, the well system (106) may facilitate the extraction of hydrocarbons (or "production") from the reservoir (102).

[0017] In some embodiments disclosed herein, the well system (106) includes a rig (101), a wellbore (120), a data gathering and analysis system (160), and a well control system ("control system") (126). The well control system (126) may control various operations of the well system (106), such as well production operations, well drilling operation, well completion operations, well maintenance operations, and reservoir monitoring, assessment and development operations. In some embodiments, the well control system (126) includes a computer system.

[0018] The rig (101) is the machine used to drill a borehole to form the wellbore (120). Major components of the rig (101) include the drilling fluid tanks, the drilling fluid pumps (e.g., rig mixing pumps), the derrick or mast, the draw works, the rotary table or top drive, the drill string, the power generation equipment and auxiliary equipment. Drilling fluid, also referred to as "drilling mud" or simply "mud," is used to facilitate drilling boreholes into the earth, such as drilling oil and natural gas wells.

[0019] In some embodiments, a bottom hole assembly (BHA) (151) is attached to the drill string (150) to suspend into the wellbore (120) for performing the well drilling operation. The bottom hole assembly (BHA) is the lowest part of the drill string (150) and includes the drill bit, drill collar, stabilizer, mud motor, etc. In one or more embodiments, the wellbore (120) may be drilled for exploration and/or production purposes. The wellbore (120) may be logged by lowering a combination of physical sensors (or sondes) downhole to acquire data that measures various rock and fluid properties, such as irradiation, density, electrical and acoustic properties.

[0020] The wellbore (120) includes a bored hole (i.e., borehole) that extends from the surface (108) towards a target zone of the formation (104), such as the reservoir (102).

The wellbore (120) may be drilled for exploration, development and production purposes. The wellbore (120) may facilitate the circulation of drilling fluids during drilling operations for the wellbore (120) to extend towards the target zone of the formation (104) (e.g., the reservoir (102)), facilitate the flow of hydrocarbon production (e.g., oil and gas) from the reservoir (102) to the surface (108) during production operations, facilitate the injection of substances (e.g., water) into the hydrocarbon-bearing formation (104) or the reservoir (102) during injection operations, or facilitate the communication of logging tools lowered into the formation (104) or the reservoir (102) during logging operations. The wellbore (120) may be logged by lowering a combination of physical sensors downhole to acquire data that measures various rock and fluid properties, such as irradiation, density, electrical and acoustic properties. The acquired data may be organized in a log format and referred to as well logs or well log data.

[0021] In some embodiments, the data gathering and analysis system (160) includes hardware and/or software with functionality for facilitating operations of the well system (106), such as well production operations, well drilling operation, well completion operations, well maintenance operations, and reservoir monitoring, assessment and development operations. For example, the data gathering and analysis system (160) may store geological and mechanical information of the formation and perform the poroelastic analysis based on user input of borehole geometry and drilling parameters. The poroelastic analysis results may then be provided to the well control system (126) to facilitate various operations of the well system (106), e.g., in a manner to mitigate a potential borehole breakout event and prevent a borehole breakout induced problem of tight hole or stuck pipe.

[0022] While the data gathering and analysis system (160) is shown at a well site, embodiments are contemplated where at least a portion of the data gathering and analysis system (160) is located away from well sites. In some embodiments, the data gathering and analysis system (160) may include a computer system that is similar to the computer system (400) described below with regard to FIG. 4 and the accompanying description.

[0023] FIG. 1B shows details of the data gathering and analysis system (160) depicted in FIG. 1A above, in accordance with one or more embodiments disclosed herein. In

one or more embodiments, one or more of the modules and/or elements shown in FIG. 1B may be omitted, repeated, and/or substituted. Accordingly, embodiments disclosed herein should not be considered limited to the specific arrangements of modules and/or elements shown in FIG. 1B.

[0024] As shown in FIG. 1B, the data gathering and analysis system (160) has multiple components, including, for example, a buffer (114), a characteristic diffusion time analyzer (111), a poroelastic analysis engine (112), and a display engine (113). Each of these components is discussed below.

[0025] In one or more embodiments, the buffer (114) may be implemented in hardware (*i.e.*, circuitry), software, or any combination thereof. The buffer (114) may be any data structure configured to store input data, output results, and intermediate data of the characteristic diffusion time analyzer (111), the poroelastic analysis engine (112), and the display engine (113). In one or more embodiments, the buffer (114) stores formation properties (115), borehole and drilling parameters (116), characteristic diffusion time (117), borehole failure critical time (118), failure region (119), and borehole operation specification (120).

[0026] In one or more embodiments, the characteristic diffusion time analyzer (111) may be implemented in hardware (*i.e.*, circuitry), software, or any combination thereof. The characteristic diffusion time analyzer (111) is configured to compute the characteristic diffusion time (117) based on the formation properties (115) and the borehole and drilling parameters (116). For example, the formation properties (115) may be obtained from a logging operation while the borehole and drilling parameters (116) may be obtained from user input.

[0027] In one or more embodiments, the poroelastic analysis engine (112) may be implemented in hardware (*i.e.*, circuitry), software, or any combination thereof. In particular, the poroelastic analysis software is used to assist drilling in challenging formations. Geological formations can demonstrate various complicated mechanical, hydraulic, thermal and chemical behaviors, which impose tremendous challenges to the drilling operations. For example, lamination causes the shale formations behave differently in different directions. The presence of natural fractures in shales degrades mechanical strength of formation and introduces complicated fluid flow phenomena

in rock mass and fractures. In salt formations, the borehole size may continue to reduce after initial stabilization such that the completion cannot be performed. The stability and integrity of wellbore is dependent on a balance between effective stresses and rock strength. Decreasing effective stresses or increasing rock strength is beneficial to the wellbore integrity. Conversely, increasing effective stresses or decreasing rock strength has detrimental effects. In fractured formations, natural fractures cause the mechanical strength of rocks to be weak and anisotropic. The fluid in the fracture introduces an additional diffusion process, which communicates with the fluid flow in the rock mass pore space, also interacts with the mechanical deformation, thus drives the evolution of stresses and pore pressure, of the rock mass. In high-pressure high-temperature (HPHT) formations, the high gradients of fluid pressure and/or temperature between the formation and wellbore fluid cause strong fluid diffusion and/or heat transfer in the near-wellbore region. Consequently, the effective stresses around wellbore show strongly nonlinear, nonmonotonic, time-dependent behaviors. The rock strength is affected by the temperature change. In chemically active shales, the rock strength and other mechanical properties and behaviors may be altered when exposed to aqueous solutions. The chemical potential difference between the drilling mud and shale-clay matrix introduces additional nonmonotonic coupled pore pressure processes around the wellbore, which causes effective stresses to evolve in real-time. As the drilling fluid invades into the formation, the drilling fluid causes chemical reactions that subsequently weaken formation mechanical strength. Because of these mechanical, hydraulic, thermal and chemical mechanisms, the rock strengths and the stresses & pore pressure around the wellbore are time dependent. Subsequently, to maintain the stability and integrity of wellbore, the weight and chemical compositions of the drilling mud in the wellbore need to be adjusted in real-time. Lack of the adjustments can lead to unexpected catastrophic failures, in both wellbore collapse and wellbore fracturing failure modes. In one or more embodiments, the poroelastic analysis software models these mechanical, hydraulic, thermal and chemical mechanisms and generates analytical solutions to wellbore stability. For example, the analytical solutions may include mud weight adjustment and/or mud composition adjustment with respect to time (i.e., real-time mud adjustment) that maintain the stability and integrity of wellbore. Analytical

solutions delivers higher efficiency and accuracy than the complicated and computation-extensive numerical models employed to handle these challenging problems in conventional method.

[0028] The poroelastic analysis engine (112) is configured to compute the borehole failure critical time (118) and the failure region (119) with respect to the characteristic diffusion time (117). For example, the borehole failure critical time (118) and the failure region (119) may be computed using a poroelastic analysis software. The poroelastic analysis software is used to calculate elastic stresses and pore pressure around the borehole that are compared with the selected failure criterion (e.g., Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-Brown criterion, Modified Lade criterion, etc.) to evaluate if a location around the borehole will fail at user specified times of interest within the characteristic diffusion time (117). These failure criteria relate to failure induced by the hydro-mechanical interaction taking place in the order of seconds, milliseconds or even microseconds in the drilling operation depending on the diffusivity of the formation. In particular, the characteristic diffusion time (117) corresponds to the undrained response period or the non-monotonic pore pressure dissipation phase of the hydro-mechanical interaction. The consequence (e.g., spalling, washout, tight hole, stuck pipe, etc.) of these failures in the field is often delayed thus only observable in the operations at later stages.

[0029] In one or more embodiments, the display engine (113) may be implemented in hardware (*i.e.*, circuitry), software, or any combination thereof. The display engine (113) is configured to render and display the failure region (119), e.g., on a driller console. The displayed failure region (119) provides drilling operators a much better idea whether they should expect a borehole breakout induced problems (e.g., spalling, washout, tight hole, stuck pipe) at later stages. Borehole breakouts are stress-induced enlargements of the wellbore cross-section. Spalling refers to borehole wall breaking off into fragments. Washout refers to borehole enlargement to exceed the original hole size or the drill bit size. Tight hole refers to the section of a borehole where larger diameter components of the drill string, such as drill pipe tool joints, drill collars, stabilizers, and the bit, may experience resistance when the driller attempts to pull them through these sections. A pipe is considered stuck during drilling operations if

it cannot be freed from the hole without damaging the pipe, and without exceeding the drilling rig's maximum allowed hook load.

[0030] Although the data gathering and analysis system (160) is shown as having four components (111, 112, 113, 114), in other embodiments, the data gathering and analysis system (160) may have more or fewer components. Further, the functionality of each component described above may be split across multiple components. Further still, each component (111, 112, 113, 114) may be utilized multiple times to carry out an iterative operation.

[0031] FIG. 2 shows a flowchart in accordance with one or more embodiments disclosed herein. One or more of the steps in FIG. 2 may be performed by the components of the well environment (100), in particular the data gathering and analysis system (160), discussed above in reference to FIGs. 1A-1B. In one or more embodiments, one or more of the steps shown in FIG. 2 may be omitted, repeated, and/or performed in a different order than the order shown in FIG. 2. Accordingly, the scope of the disclosure should not be considered limited to the specific arrangement of steps shown in FIG. 2.

[0032] The method flowchart describes a procedure that can capture the failure regions occurring around a borehole at the critical moments of failure thus provide a complete picture of borehole collapse risk in the wellbore stability analysis using analytical elastic stress solutions. The complete picture of borehole collapse risk can be provided for both a previously drilled well and a to-be drilled new well. For a previously drilled well with collapse observed, the method provides an explanation of the cause of the collapse that cannot be explained by elastic analysis. For a new well, the method captures the collapse that cannot be predicted by the elastic analysis. In particular, the most severe failures may occur at the undrained response period, or during the non-monotonic pore pressure dissipation phase of a hydro-mechanical interaction occurring around a borehole in a drilling operation.

[0033] Initially in Step 201, the characteristic diffusion time of a borehole is determined. The characteristic diffusion time of the borehole corresponds to one of the undrained response period or the non-monotonic pore pressure dissipation phase of the borehole. During the undrained response period, the fluid does not flow; it

happens instantaneously. The pore pressure rises up due to volumetric contraction or drops due to volumetric expansion of rock mass. In the non-monotonic pore pressure dissipation period, unsteady fluid flow takes place due to local pore pressure gradient and fluid-mechanical interaction. This period ends when the fluid flow reaches steady state. Specifically, the undrained response period, or the non-monotonic pore pressure dissipation phase, starts from time 0 till the time reaches the characteristic diffusion time of a borehole. Time 0 refers to the moment when the rock inside the borehole segment of interest is excavated/drilled.

[0034] In one or more embodiments, the characteristic diffusion time of the borehole is computed using Eq. (1) through Eq. (6) below.

[0035] The time scale of diffusion process in a porous medium may be characterized by the diffusion coefficient:

[0036]
$$c = \frac{k}{S} \quad \text{Eq. (1)}$$

[0037] where k is the formation permeability (mobility coefficient, intrinsic permeability divided by fluid viscosity); S is the storativity, defined by:

[0038]
$$S = \frac{(1-v_u)(1-2v)}{M(1-v)(1-2v_u)} \quad \text{Eq. (2)}$$

[0039] where M is the Biot modulus, defined by:

[0040]
$$M = \frac{2G(v_u - v)}{\alpha^2(1-2v_u)(1-2v)} \quad \text{Eq. (3)}$$

[0041] where v_u is rock's undrained Poisson's ratio; G is rock's shear modulus. Note the relationship between [Young's modulus (E), Poisson's ratio (v)] and [bulk modulus (K), shear modulus (G)] are:

[0042]
$$G = \frac{E}{2(1+v)} \quad \text{Eq. (4)}$$

$$K = \frac{E}{3(1-2v)} \quad \text{Eq. (5)}$$

[0043] The characteristic diffusion time of the borehole is:

[0044]
$$t_c = \frac{R^2}{c} \quad \text{Eq. (6)}$$

[0045] In Step 202, the critical time of the borehole is determined based on a selected failure criterion (*e.g.*, Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-

Brown criterion, Modified Lade criterion, etc.). For example, the Mohr–Coulomb (MC) failure criterion is a set of linear equations in principal stress space describing the conditions for which an isotropic material will fail, with any effect from the intermediate principal stress being neglected.

[0046] In one or more embodiments, the critical time is determined by computing the pore pressure distribution around the borehole during the undrained response period, or the non-monotonic pore pressure dissipation phase. In other words, the pore pressure distribution around the borehole is computed during the time period $[0, t_c]$. In one or more embodiments, the pore pressure distribution around the borehole is computed using a poroelastic analysis software to determine the critical azimuthal angles (θ_{crit}) where the maximum pore pressure is observed near the borehole. Accordingly, the maximum pore pressure at the critical azimuthal angles (θ_{crit}) is computed, using the poroelastic analysis software, as a function of time during the time period $[0, t_c]$. The time that yields the peak pore pressure from the poroelastic analysis software is referred to as the critical time (t_{crit}) when the most severe failure (i.e., based on the selected failure criterion such as Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-Brown criterion, Modified Lade criterion, etc.) is expected to occur.

[0047] In Step 203, the failure regions of the borehole occurring at the critical time t_{crit} are identified or otherwise determined based on the selected failure criterion (e.g., Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-Brown criterion, Modified Lade criterion, etc.). In one or more embodiments, the failure regions of the borehole at the critical time t_{crit} are determined using the poroelastic analysis software.

[0048] In Step 204, an operation of a well system is performed based on the failure regions of the borehole. In one or more embodiments, the failure regions correspond to predicted failure regions around a target location where a new well is to be drilled. In such embodiments, the drilling parameters (e.g., mud weight and/or mud composition) and equipment are defined based on the predicted failure regions and used to drill the borehole in a manner to mitigate a potential borehole breakout event in the failure region. In conventional methods, the stresses around a new well are calculated using elastic solution, and the mud weight is designed based on these

stresses. Because the undrained response and the poroelastic response are not considered in the elastic solution, the mud weight designed using the elastic solution of conventional methods cannot maintain the wellbore stability. Instead, with the poroelastic solution being used in the calculation of the safe mud weight, the critical time after drilling when the collapse may most possibly take place can be identified. In one or more embodiments, the failure regions correspond to predicted failure regions around an existing well that was previously drilled. In such embodiments, the maintenance parameters (e.g., real-time adjusted mud weight and/or composition) and equipment are defined based on the predicted failure regions and used to perform preventive maintenance of the borehole to mitigate any potential borehole breakout event.

[0049] FIGs. 3A-3K show an implementation example in accordance with one or more embodiments. The implementation example shown in FIGs. 3A-3K is based on the system and method flowchart described in reference to FIGs. 1A, 1B, and 2 above. In one or more embodiments, one or more of the modules and/or elements shown in FIGs. 3A-3B may be omitted, repeated, and/or substituted. Accordingly, embodiments disclosed herein should not be considered limited to the specific arrangements of modules and/or elements shown in FIGs. 3A-3B.

[0050] The implementation example shown in FIGs. 3A-3B relates to an example borehole drilled in a shale formation, the relevant geometric information is listed in LIST 1 below.

LIST 1

True vertical depth (TVD) of interest = 4724 m

Borehole radius = 0.0747 m

Borehole inclination angle = 0°

Borehole azimuth = 0°

[0051] The hydraulic and mechanical properties of formations are listed in LIST 2 below.

LIST 2

Young's modulus = 41.4 GPa

Poisson's ratio = 0.22

Undrained Poisson's ratio = 0.46

Biot coefficient = 0.8

Permeability = 0.001 mD

Fluid Viscosity = 1 cP

[0052] The in-situ stresses and pore pressure and wellbore mud weight are listed in LIST 3 below.

LIST 3

Vertical stress (SV) = 117.5 MPa

Maximum horizontal stress (SHmax) = 138.9 MPa

Minimum horizontal stress (Shmin) = 85.5 MPa

Pore pressure (Pp) = 52 MPa

Wellbore mud weight (MW) = 70 pcf

[0053] In the example poroelastic analysis below, borehole responses (i.e., pore pressure distribution around the borehole) in the potential failure regions are initially analyzed at time points beyond the undrained response period or the non-monotonic pore pressure dissipation phase, i.e., the time period $[0, t_c]$. FIG. 3A shows the input parameters to the poroelastic analysis software based on LISTs 1-3 above. The input parameters include analysis settings (301), wellbore geometry (302), elastic properties (303), in-situ stresses and pore pressures (304), failure criteria and strength properties (305), poroelastic properties (306), and time after wellbore drilling (307). In particular, the input parameters specify the failure regions to be determined based on the Mohr-Coulomb criterion within an annular region surrounding the borehole extending radially to 1.03 times the borehole radius. Further, the input parameters specify the failure regions to be determined at the time of interest of 15 min, 2 hours, 1 day and 5 days after the drilling operation. For example, in-situ stresses and pore pressures (304) correspond the target zone where a new well is planned to be drilled. A large-scale three-dimensional mechanical earth model (MEM) for the formation containing the new well to be drilled is first calibrated with the in-situ stresses of existing wells and other known data, then the in-situ stresses corresponding to the new

well path are extracted from MEM and used for wellbore stability analysis and mud weight calculation.

[0054] FIGs. 3B and 3C show the output result of the poroelastic analysis software based on the input parameters of FIG. 3A. Specifically, FIG. 3B shows the failure regions (320) near the borehole (120) according to the legend (300) at 15 minutes after wellbore drilling. FIG. 3C shows the failure regions (330) near the borehole (120) according to the legend (300) at 5 days after wellbore drilling. As noted above, the rock inside the borehole segment of interest is assumed to be excavated/drilled instantaneously, i.e., at time 0. Accordingly, 15 minutes is the time lapse after time 0. Further, the wellbore may be an existing wellbore (e.g., borehole (120)), to diagnose observed problems, or a new well to design drilling mud weight and predict wellbore stability. The analysis is performed using a poroelastic analysis software. The scale of the annular region of the borehole (120) is expanded relative to the borehole itself to illustrate details of the failure regions.

[0055] As shown in FIGs. 3B and 3C, the failure regions (320) and (330) are very shallow (e.g., 0.5") relative the borehole size (e.g., 5") during the time period (15 minute, 5 days), no significant borehole breakout induced problems are expected. However, a high risk might have been overlooked because this initial analysis does not capture the more critical moments before 15 minutes after drilling when much more severe failure may occur.

[0056] Additional poroelastic analysis is then performed prior to 15 minutes after drilling to be during the undrained response period or the non-monotonic pore pressure dissipation phase. FIG. 3D shows the input parameters to the poroelastic analysis software that are similar to FIG. 3A above. Note that the times of interest are specified as 0.0001 s, 0.1 s, 10 s and 100 s instead of 15 min, 2 hours, 1 day and 5 days as in FIG. 3A. The poroelastic analysis is illustrated in Step 1 through Step 3 below.

[0057] Step 1. Compute the characteristic diffusion time:

[0058] Substituting the relevant properties from FIG. 3D into Eq. (1) – Eq. (6) gives:

[0059]
$$c = 5.78 \times 10^{-5} \text{ m}^2/\text{s}$$

[0060] $t_c = 96.5 \text{ s}$

[0061] Step 2. Set four times of interest:

[0062] $t_1 = 0.0001 \text{ s}$

[0063] $t_2 = 0.1 \text{ s}$

[0064] $t_3 = 10 \text{ s}$

[0065] $t_4 = 100 \text{ s}$

[0066] The azimuthal variation of pore pressure around the borehole at four different times (0.0001 s, 0.1 s, 10 s and 100 s) are shown in FIG. 3E, from which the critical wellbore angle is identified to be 180° and 0.0001 s (i.e., t_1) is determined as the critical time. The critical time t_1 identified in FIG. 3E corresponds to the potential critical moment when the most severe failure may occur.

[0067] FIG. 3F shows the radial variation of pore pressure at the angle of 180° at four different times (0.0001 s, 0.1 s, 10 s and 100 s). It is observed that the pore pressure in the near wellbore region first builds up then dissipates, its distribution at early time is non-uniform in either azimuthal or radial direction.

[0068] In response to the build-up and dissipation of pore pressure, the effective radial stress and tangential stress at this angle decreases then increase as time progresses, as shown in FIGs. 3G and 3H. In particular, FIG. 3G shows the azimuthal variation of effective radial stress around wellbore at times of 0.0001 s, 0.1 s, 10 s and 100 s, and FIG. 3H shows azimuthal variation of effective tangential stress around wellbore at times of 0.0001 s, 0.1 s, 10 s and 100 s.

[0069] Step 3. Compute the failure regions at the critical time $t_1 = 0.0001 \text{ s}$:

[0070] The failure regions at t_1 is shown in FIG. 3I, which shows a large failure region (390) around the borehole (120). This implies that some borehole breakout induced issues, such as “tight hole”, “stuck pipe”, etc., may be encountered in the operations at later stages. In particular, borehole breakouts are stress-induced enlargements of the wellbore cross-section. The failure regions at t_1 shown in FIG. 3I corresponds to the most critical failure scenario during the drilling process. FIG. 3I may be displayed on a driller console to give drilling operators a better idea whether they should expect

a borehole breakout induced problems (e.g., spalling, washout, tight hole, stuck pipe) at later stages. Accordingly, the drilling operations may exercise mitigation measures to prevent these latent borehole breakout induced problems. For example, the mitigation measures to prevent the breakout include using mud weights obtained from poroelastic analysis using the poroelastic analysis software.

[0071] FIGs. 3J and 3K show the failure regions (391) and (392) at $t_3 = 10$ s and $t_4 = 100$ s, respectively. Note that $t_4 = 100$ s corresponds to the borehole's characteristic diffusion time where the corresponding failure region (392) approaches the failure regions (320) and (330) at 15 minutes and 5 days, as shown in FIGs. 3B and 3C above.

[0072] Embodiments may be implemented on a computing system. FIG. 4 depicts a block diagram) of a computing system (400) including a computer (402) used to provide computational functionalities associated with described machine learning networks, algorithms, methods, functions, processes, flows, and procedures as described in this disclosure, according to one or more embodiments. The illustrated computer (402) is intended to encompass any computing device such as a server, desktop computer, laptop/notebook computer, wireless data port, smart phone, personal data assistant (PDA), tablet computing device, one or more processors within these devices, or any other suitable processing device, including both physical or virtual instances (or both) of the computing device. Additionally, the computer (402) may include a computer that includes an input device, such as a keypad, keyboard, touch screen, or other device that can accept user information, and an output device that conveys information associated with the operation of the computer (402), including digital data, visual, or audio information (or a combination of information), or a GUI.

[0073] The computer (402) can serve in a role as a client, network component, a server, a database or other persistency, or any other component (or a combination of roles) of a computer system for performing the subject matter described in the instant disclosure. The illustrated computer (402) is communicably coupled with a network (430). In some implementations, one or more components of the computer (402) may be configured to operate within environments, including cloud-computing-based, local, global, or other environment (or a combination of environments).

- [0074] At a high level, the computer (402) is an electronic computing device operable to receive, transmit, process, store, or manage data and information associated with the described subject matter. According to some implementations, the computer (402) may also include or be communicably coupled with an application server, e-mail server, web server, caching server, streaming data server, business intelligence (BI) server, or other server (or a combination of servers).
- [0075] The computer (402) can receive requests over network (430) from a client application (for example, executing on another computer (402)) and responding to the received requests by processing the said requests in an appropriate software application. In addition, requests may also be sent to the computer (402) from internal users (for example, from a command console or by other appropriate access method), external or third-parties, other automated applications, as well as any other appropriate entities, individuals, systems, or computers.
- [0076] Each of the components of the computer (402) can communicate using a system bus (403). In some implementations, any or all of the components of the computer (402), both hardware or software (or a combination of hardware and software), may interface with each other or the interface (404) (or a combination of both) over the system bus (403) using an application programming interface (API) (412) or a service layer (413) (or a combination of the API (412) and service layer (413)). The API (412) may include specifications for routines, data structures, and object classes. The API (412) may be either computer-language independent or dependent and refer to a complete interface, a single function, or even a set of APIs. The service layer (413) provides software services to the computer (402) or other components (whether or not illustrated) that are communicably coupled to the computer (402). The functionality of the computer (402) may be accessible for all service consumers using this service layer. Software services, such as those provided by the service layer (413), provide reusable, defined business functionalities through a defined interface. For example, the interface may be software written in JAVA, C++, or other suitable language providing data in extensible markup language (XML) format or another suitable format. While illustrated as an integrated component of the computer (402), alternative implementations may illustrate the API (412) or the service layer (413) as stand-alone components in relation to other components of the computer (402) or

other components (whether or not illustrated) that are communicably coupled to the computer (402). Moreover, any or all parts of the API (412) or the service layer (413) may be implemented as child or sub-modules of another software module, enterprise application, or hardware module without departing from the scope of this disclosure.

[0077] The computer (402) includes an interface (404). Although illustrated as a single interface (404) in FIG. 4, two or more interfaces (404) may be used according to particular needs, desires, or particular implementations of the computer (402). The interface (404) is used by the computer (402) for communicating with other systems in a distributed environment that are connected to the network (430). Generally, the interface (404) includes logic encoded in software or hardware (or a combination of software and hardware) and operable to communicate with the network (430). More specifically, the interface (404) may include software supporting one or more communication protocols, such as the Wellsite Information Transfer Specification (WITS) protocol, associated with communications such that the network (430) or interface's hardware is operable to communicate physical signals within and outside of the illustrated computer (402).

[0078] The computer (402) includes at least one computer processor (405). Although illustrated as a single computer processor (405) in FIG. 4, two or more processors may be used according to particular needs, desires, or particular implementations of the computer (402). Generally, the computer processor (405) executes instructions and manipulates data to perform the operations of the computer (402) and any algorithms, methods, functions, processes, flows, and procedures as described in the instant disclosure.

[0079] The computer (402) also includes a memory (406) that holds data for the computer (402) or other components (or a combination of both) that can be connected to the network (430). For example, memory (406) can be a database storing data consistent with this disclosure. Although illustrated as a single memory (406) in FIG. 4, two or more memories may be used according to particular needs, desires, or particular implementations of the computer (402) and the described functionality. While memory (406) is illustrated as an integral component of the computer (402), in alternative implementations, memory (406) can be external to the computer (402).

[0080] The application (407) is an algorithmic software engine providing functionality according to particular needs, desires, or particular implementations of the computer (402), particularly with respect to functionality described in this disclosure. For example, application (407) can serve as one or more components, modules, applications, etc. Further, although illustrated as a single application (407), the application (407) may be implemented as multiple applications (407) on the computer (402). In addition, although illustrated as integral to the computer (402), in alternative implementations, the application (407) can be external to the computer (402).

[0081] There may be any number of computers (402) associated with, or external to, a computer system containing a computer (402), wherein each computer (402) communicates over network (430). Further, the term "client," "user," and other appropriate terminology may be used interchangeably as appropriate without departing from the scope of this disclosure. Moreover, this disclosure contemplates that many users may use one computer (402), or that one user may use multiple computers (402).

[0082] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the disclosure as disclosed herein. Accordingly, the scope of the disclosure should be limited only by the attached claims.

CLAIMS

What is claimed is:

1. A method for performing a borehole operation, comprising:
 - determining (201) a characteristic diffusion time (117) that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole;
 - determining (202), based on a pre-determined failure criterion, a critical time (118) of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time (117);
 - identifying (203) a failure region (119) of the failure occurring at the critical time (118) of the borehole; and
 - performing (204), based on at least the identified failure region (119), the borehole operation.
2. The method of claim 1,
 - wherein the borehole is an existing borehole,
 - wherein the failure that occurred during previous drilling of the borehole results in a potential borehole breakout event, and
 - wherein the borehole operation comprises a maintenance operation to mitigate the potential borehole breakout event.
3. The method of claim 1 or 2, further comprising:
 - determining, based on at least the identified failure region (119), an adjusted mud weight with respect to time,
 - wherein the borehole operation is performed further based on the adjusted mud weight with respect to time.
4. The method of claim 1 or 3 when not dependent on claim 2,
 - wherein the borehole is a planned borehole to be drilled,
 - wherein the failure is predicted to occur during a drilling operation of the planned borehole to result in a potential borehole breakout event, and

wherein the borehole operation comprises the drilling operation that is performed based on drilling parameters (116) and equipment that are selected to mitigate the potential borehole breakout event.

5. The method of claim 4, further comprising:
specifying, based on the identified failure region (119), the drilling parameters (116) and the equipment of the drilling operation.
6. The method of any one of claims 1 to 5,
wherein the pre-determined failure criterion comprises one of Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-Brown criterion, and Modified Lade criterion.
7. The method of any one of claims 1 to 6, wherein performing the borehole operation comprises preventing a borehole breakout induced problem of tight hole or stuck pipe.
8. A data gathering and analysis system (160), comprising:
a computer processor (405); and
memory storing instructions, when executed, causing the computer processor (405) to:
determine (201) a characteristic diffusion time (117) that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole;
determine (202), based on a pre-determined failure criterion, a critical time (118) of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time (117);
identify (203) a failure region (119) of the failure occurring at the critical time (118) of the borehole; and
perform (204), based at least on the identified failure region (119), a borehole operation.
9. The data gathering and analysis system of claim 8,
wherein the borehole is an existing borehole,
wherein the failure that occurred during previous drilling of the borehole results in a potential borehole breakout event, and
wherein the borehole operation comprises a maintenance operation to mitigate the potential borehole breakout event.

10. The data gathering and analysis system of claim 8 or 9, wherein the instructions, when executed, further cause the computer processor (405) to:
 - determine, based on at least the identified failure region (119), an adjusted mud weight with respect to time,
 - wherein the borehole operation is performed further based on the adjusted mud weight with respect to time.
11. The data gathering and analysis system of claim 8 or 10 when not dependent on claim 9, wherein the borehole is a planned borehole to be drilled,
 - wherein the failure is predicted to occur during a drilling operation of the planned borehole to result in a potential borehole breakout event, and
 - wherein the borehole operation comprises the drilling operation that is performed based on drilling parameters (116) and equipment that are selected to mitigate the potential borehole breakout event.
12. The data gathering and analysis system of claim 11, wherein instructions, when executed, further cause the computer processor (405) to:
 - specify, based on the identified failure region (119), the drilling parameters (116) and the equipment of the drilling operation.
13. The data gathering and analysis system of any one of claims 8 to 12,
 - wherein the pre-determined failure criterion comprises one of Mohr-Coulomb criterion, Drucker-Prager criterion, Hoek-Brown criterion, and Modified Lade criterion.
14. The data gathering and analysis system of any one of claims 8 to 13, wherein performing the borehole operation comprises preventing a borehole breakout induced problem of tight hole or stuck pipe.
15. A well system (106) comprising:
 - a rig (101) for drilling a borehole; and
 - a data gathering and analysis system (160) comprising functionality for:
 - determining (201) a characteristic diffusion time (117) that corresponds to an undrained response period or a non-monotonic pore pressure dissipation phase of a porous medium surrounding a borehole;

determining (202), based on a pre-determined failure criterion, a critical time (118) of the borehole that corresponds to when a failure of the porous medium occurs within the characteristic diffusion time (117);
identifying (203) a failure region (119) of the failure occurring at the critical time (118) of the borehole; and
performing (204), using the rig (101) and based at least on the identified failure region (119), a borehole operation.

16. The well system of claim 15,
wherein the borehole is an existing borehole,
wherein the failure that occurred during previous drilling of the borehole results in a potential borehole breakout event, and
wherein the borehole operation comprises a maintenance operation to mitigate the potential borehole breakout event.
17. The well system of claim 15 or 16, the data gathering and analysis system (160) further comprising functionality for:
determining, based on at least the identified failure region (119), an adjusted mud weight with respect to time,
wherein the borehole operation is performed further based on the adjusted mud weight with respect to time.
18. The well system of claim 15 or claim 17 when not dependent on claim 16,
wherein the borehole is a planned borehole to be drilled,
wherein the failure is predicted to occur during a drilling operation of the planned borehole to result in a potential borehole breakout event, and
wherein the borehole operation comprises the drilling operation that is performed based on drilling parameters (116) and equipment that are selected to mitigate the potential borehole breakout event.
19. The well system of claim 18, the data gathering and analysis system (160) further comprising functionality for:
specifying, based on the identified failure region (119), the drilling parameters (116) and the equipment of the drilling operation.

20. The well system of any one of claims 15 to 19,
wherein the pre-determined failure criterion comprises one of Mohr-Coulomb criterion,
Drucker-Prager criterion, Hoek-Brown criterion, and Modified Lade criterion,
and
wherein performing the borehole operation comprises preventing a borehole breakout
induced problem of tight hole or stuck pipe.

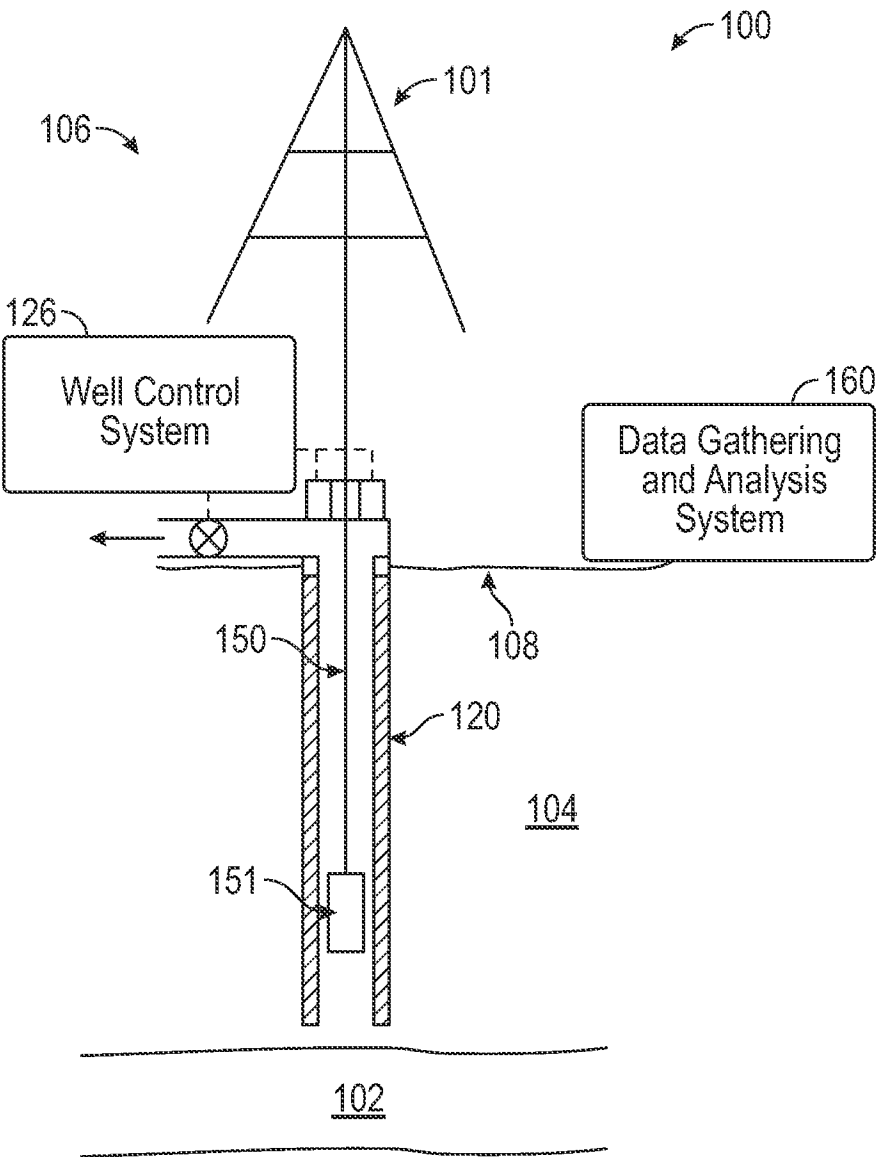


FIG. 1A

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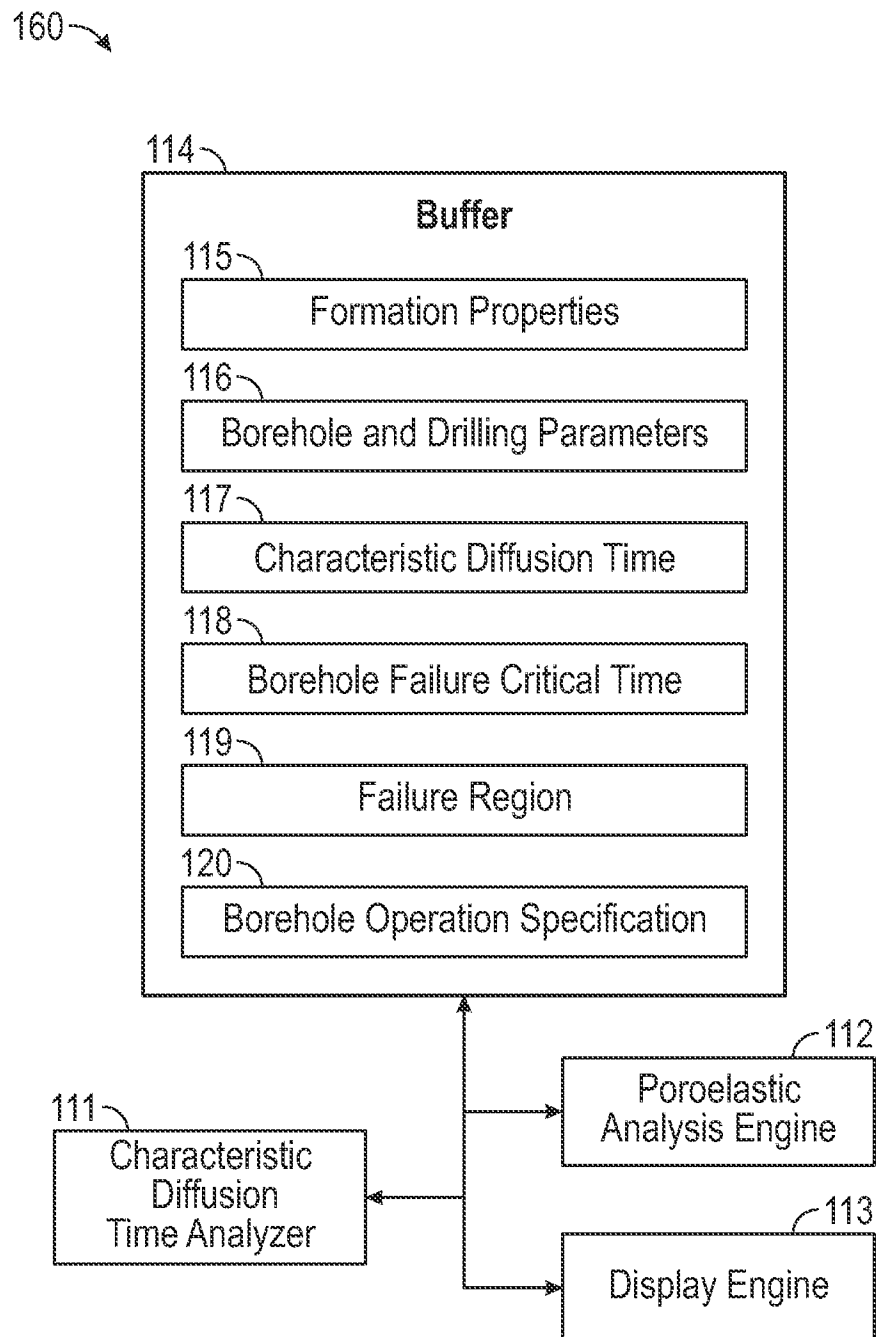


FIG. 1B

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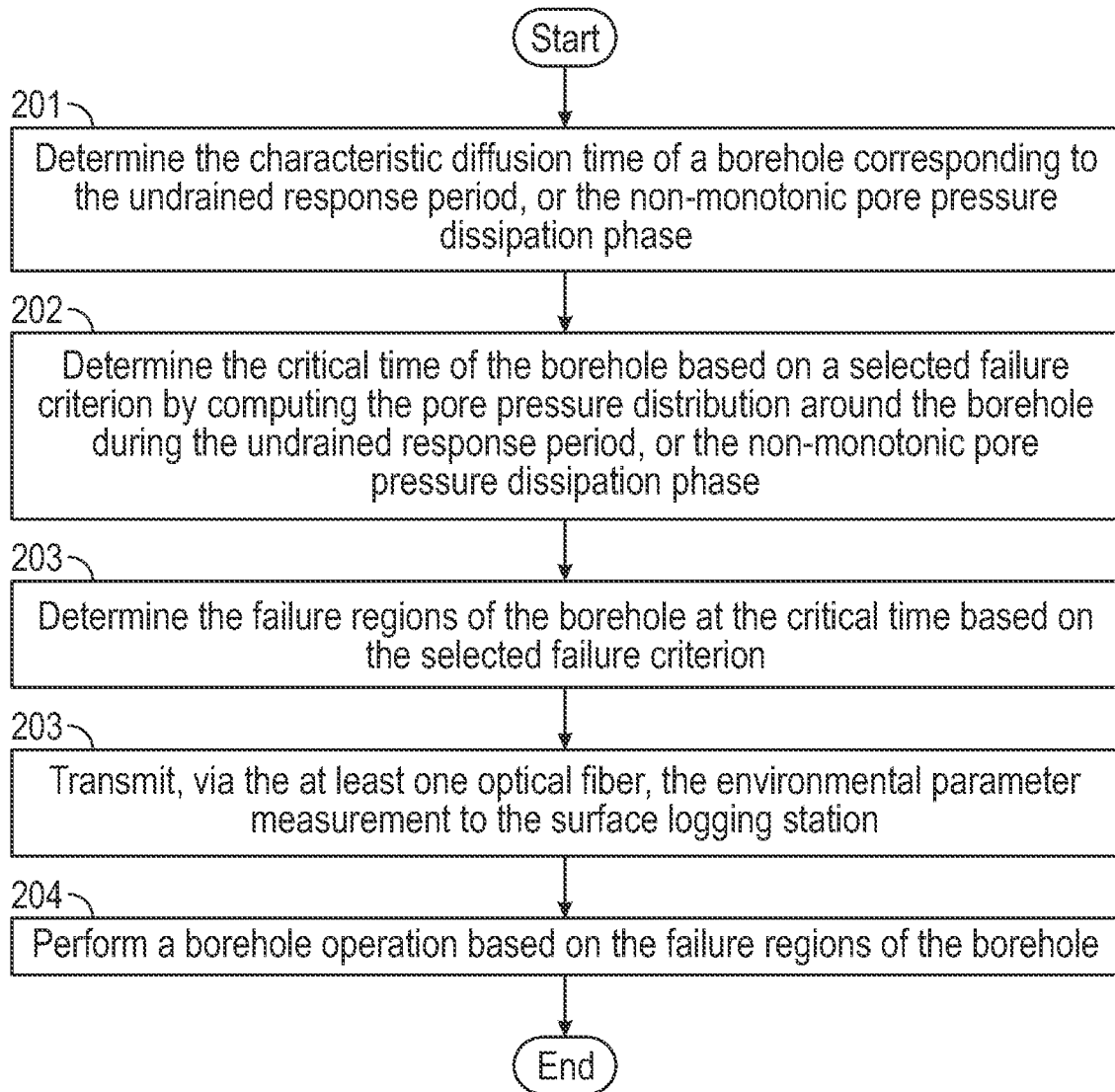


FIG. 2

301

ANALYSIS SETTINGS

WELLBORE STRESS MODEL

TIME-DEPENDENT STRESS (POROELASTIC)▼

BOREHOLE CONDITION

PERMEABLE▼

RADIAL RATIO

1.03

☐ WEAK BEDDING PLANE ANALYSIS

☐ WITH BREAKOUT ANGLE

30 DEG▼

302

WELLBORE GEOMETRY

TVD

4.7244 M▼

BOREHOLE RADIUS

0.0747 M▼

INCLINATION

0 DEG▼

AZIMUTH

0 DEG▼

303

ELASTIC PROPERTIES

YOUNG'S MODULUS

4.137E+10 PA▼

POISSON'S RATIO

0.22

304

IN-SITU STRESSES & PORE PRESSURE

OVERBURDEN STRESS GRADIENT

24.883 KPAM▼

MAX HORIZONTAL STRESS GRADIENT

29.407 KPAM▼

MIN HORIZONTAL STRESS GRADIENT

18.096 KPAM▼

PORE PRESSURE GRADIENT

13.572 KPAM▼

MAX HORIZONTAL STRESS AZIMUTH

90 DEG▼

MUD WEIGHT

70 PCF▼

305

FAILURE CRITERIA & STRENGTH PROPERTIES

FAILURE CRITERION

MOHR-COULOMB▼

SHEAR STRENGTH PARAMETERS

UCS & FRICTION ANGLE▼

UNIAXIAL COMP. STRENGTH (UCS)

68.948 MPA▼

COHESION

14.28 MPA▼

FRICTION ANGLE

46 DEG▼

TENSILE STRENGTH

1.000 MPA▼

306

POROELASTIC PROPERTIES

BIOT'S COEFFICIENT

0.8

UNDRAINED POISSON'S RATIO

0.46

PERMEABILITY

0.001 MD▼

VISCOSITY

1 CP▼

307

TIME AFTER WELLBORE DRILLING

TIME INSTANCE #1

15 MIN▼

TIME INSTANCE #2

2 HR▼

TIME INSTANCE #3

1 DAY▼

TIME INSTANCE #4

5 DAY▼

FIG. 3A

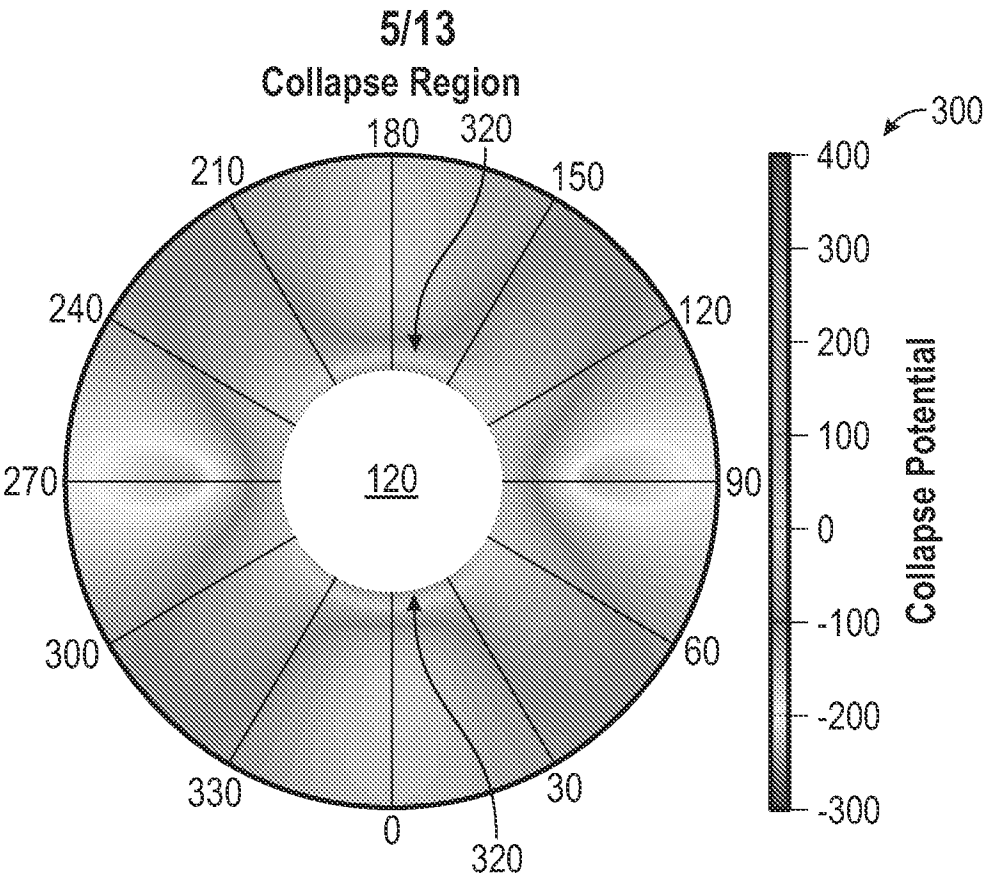


FIG. 3B

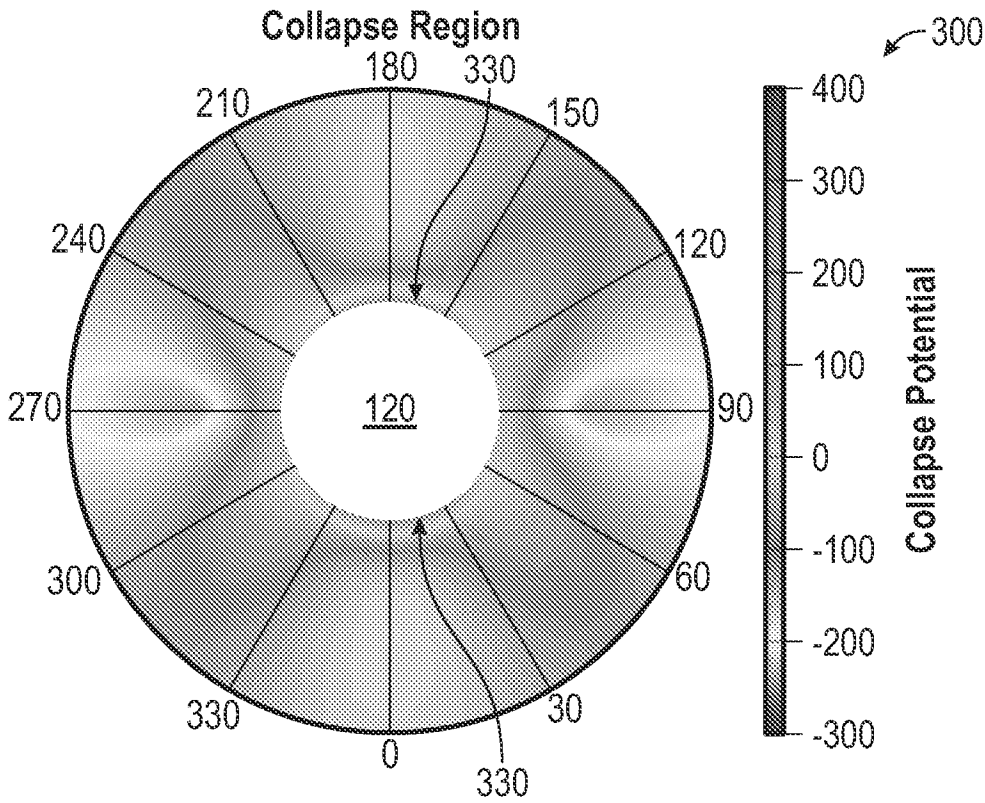


FIG. 3C

<table><tr><td colspan="2">ANALYSIS SETTINGS</td></tr><tr><td>WELLBORE STRESS MODEL</td><td></td></tr><tr><td>TIME-DEPENDENT STRESS (POROELASTIC)</td><td>▼</td></tr><tr><td>BOREHOLE CONDITION</td><td>▼</td></tr><tr><td>PERMEABLE</td><td></td></tr><tr><td>RADIAL RATIO</td><td>1.03</td></tr><tr><td>☐ WEAK BEDDING PLANE ANALYSIS</td><td></td></tr><tr><td>☐ WITH BREAKOUT ANGLE</td><td></td></tr><tr><td></td><td>30 DEG ▼</td></tr></table>	ANALYSIS SETTINGS		WELLBORE STRESS MODEL		TIME-DEPENDENT STRESS (POROELASTIC)	▼	BOREHOLE CONDITION	▼	PERMEABLE		RADIAL RATIO	1.03	☐ WEAK BEDDING PLANE ANALYSIS		☐ WITH BREAKOUT ANGLE			30 DEG ▼	<table><tr><td colspan="2">IN-SITU STRESSES & PORE PRESSURE</td></tr><tr><td>OVERBURDEN STRESS GRADIENT</td><td>1.1 PSI/FT ▼</td></tr><tr><td>MAX HORIZONTAL STRESS GRADIENT</td><td>1.3 PSI/FT ▼</td></tr><tr><td>MIN HORIZONTAL STRESS GRADIENT</td><td>0.8 PSI/FT ▼</td></tr><tr><td>PORE PRESSURE GRADIENT</td><td>0.6 PSI/FT ▼</td></tr><tr><td>MAX HORIZONTAL STRESS AZIMUTH</td><td>90 DEG ▼</td></tr><tr><td>MUD WEIGHT</td><td>70 PCF ▼</td></tr></table>	IN-SITU STRESSES & PORE PRESSURE		OVERBURDEN STRESS GRADIENT	1.1 PSI/FT ▼	MAX HORIZONTAL STRESS GRADIENT	1.3 PSI/FT ▼	MIN HORIZONTAL STRESS GRADIENT	0.8 PSI/FT ▼	PORE PRESSURE GRADIENT	0.6 PSI/FT ▼	MAX HORIZONTAL STRESS AZIMUTH	90 DEG ▼	MUD WEIGHT	70 PCF ▼	<table><tr><td colspan="2">POROELASTIC PROPERTIES</td></tr><tr><td>BIOT'S COEFFICIENT</td><td>0.8</td></tr><tr><td>UNDRAINED POISSON'S RATIO</td><td>0.46</td></tr><tr><td>PERMEABILITY</td><td>0.001 MD ▼</td></tr><tr><td>VISCOSITY</td><td>1 CP ▼</td></tr></table>	POROELASTIC PROPERTIES		BIOT'S COEFFICIENT	0.8	UNDRAINED POISSON'S RATIO	0.46	PERMEABILITY	0.001 MD ▼	VISCOSITY	1 CP ▼	<table><tr><td colspan="2">TIME AFTER WELLBORE DRILLING</td></tr><tr><td>TIME INSTANCE #1</td><td>1E-4 SEC ▼</td></tr><tr><td>TIME INSTANCE #2</td><td>0.1 SEC ▼</td></tr><tr><td>TIME INSTANCE #3</td><td>10 SEC ▼</td></tr><tr><td>TIME INSTANCE #4</td><td>100 SEC ▼</td></tr></table>	TIME AFTER WELLBORE DRILLING		TIME INSTANCE #1	1E-4 SEC ▼	TIME INSTANCE #2	0.1 SEC ▼	TIME INSTANCE #3	10 SEC ▼	TIME INSTANCE #4	100 SEC ▼
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<table><tr><td colspan="2">ELASTIC PROPERTIES</td></tr><tr><td>YOUNG'S MODULUS</td><td>4.137E+10 PA ▼</td></tr><tr><td>POISSON'S RATIO</td><td>0.22</td></tr></table>	ELASTIC PROPERTIES		YOUNG'S MODULUS	4.137E+10 PA ▼	POISSON'S RATIO	0.22																																																	
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POISSON'S RATIO	0.22																																																						

FIG. 3D

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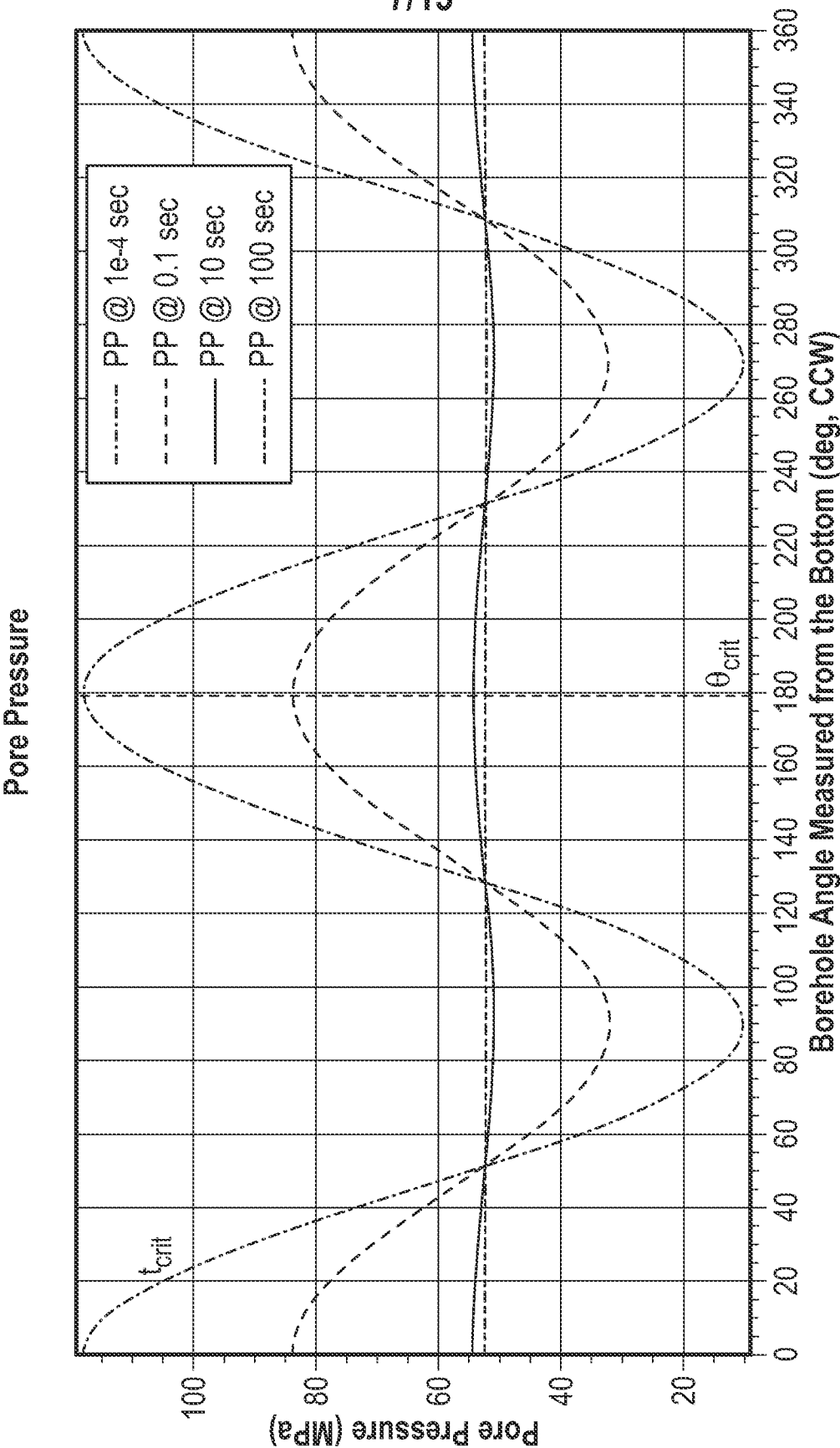


FIG. 3E

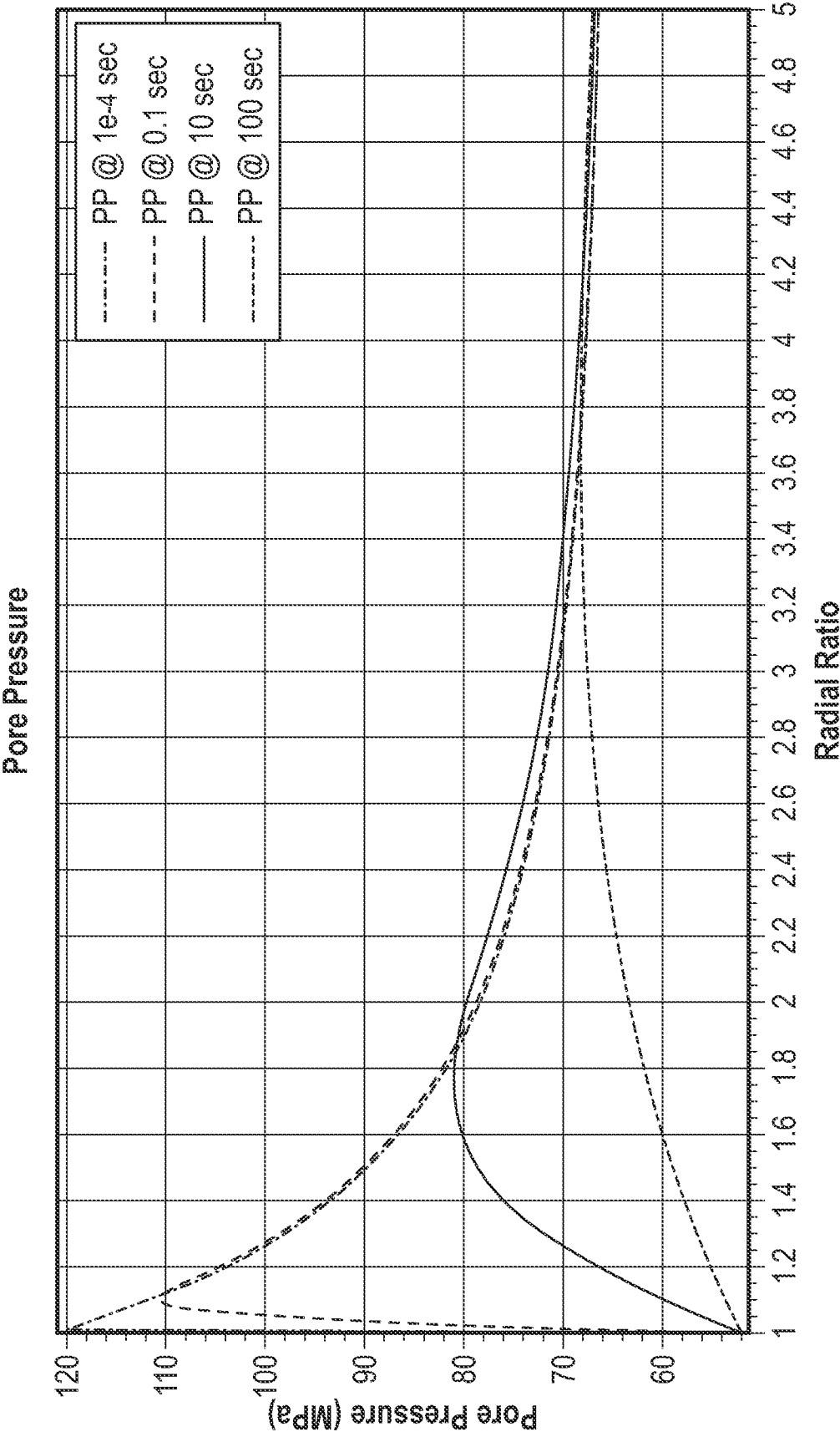


FIG. 3F

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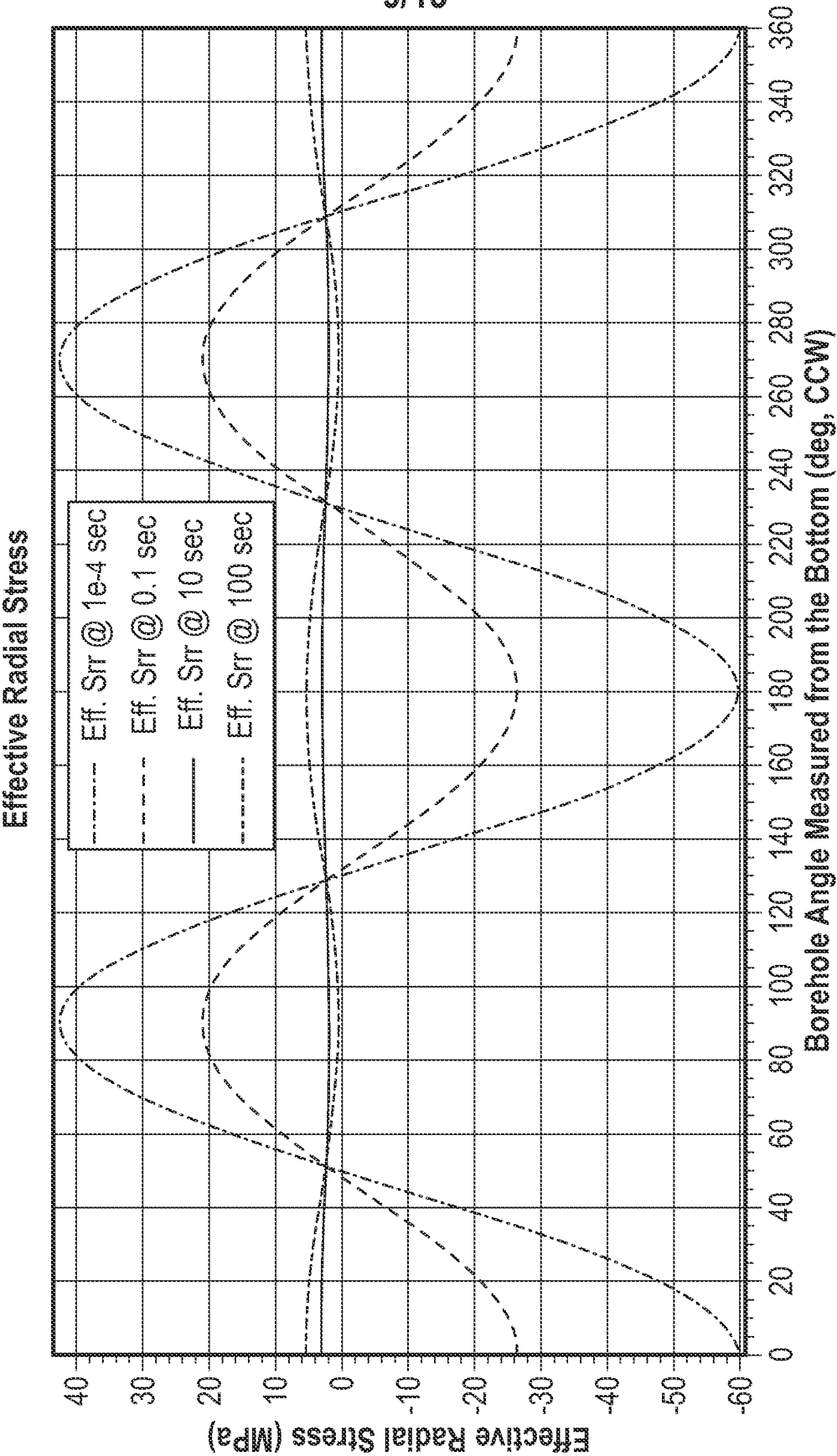


FIG. 3G

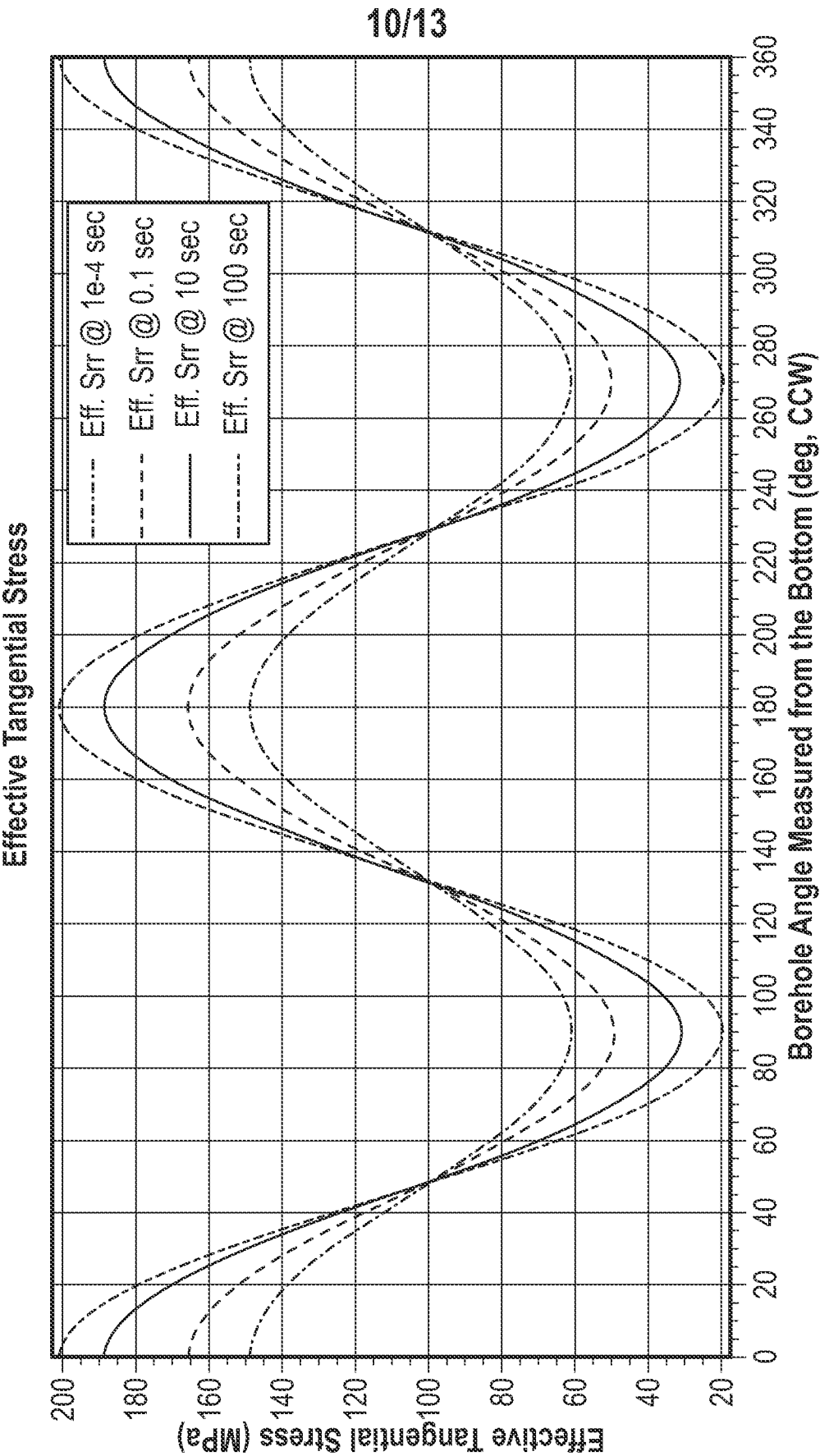


FIG. 3H

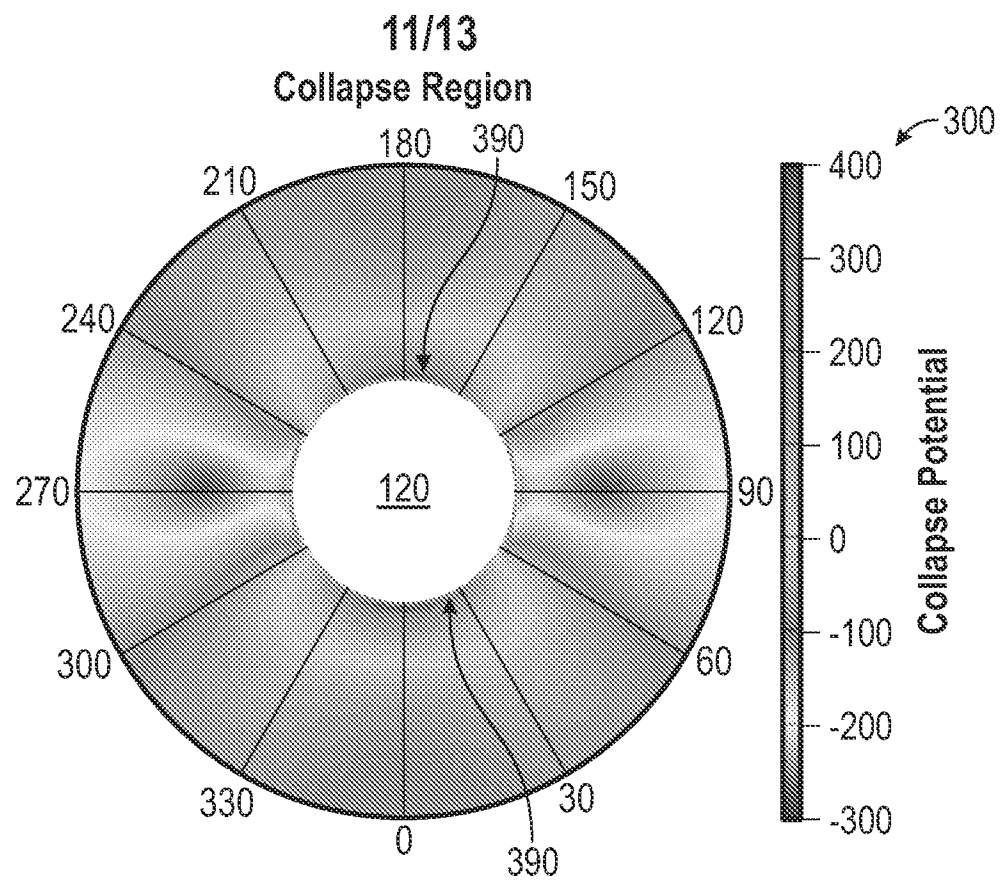


FIG. 31

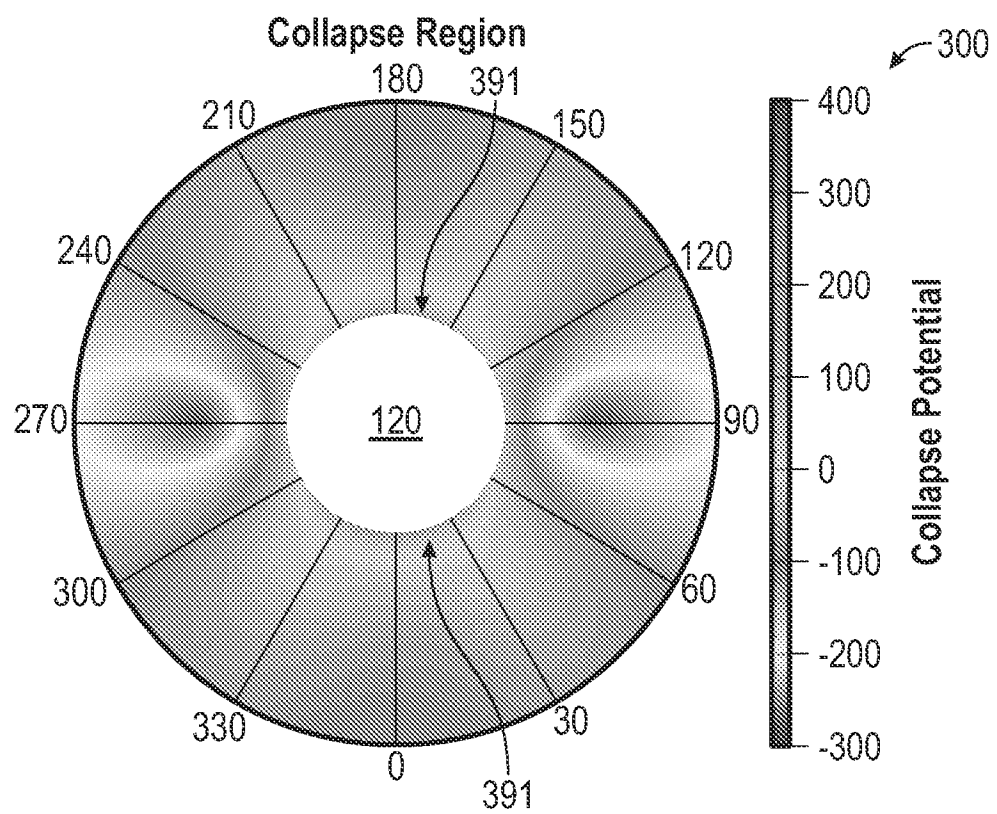


FIG. 3J

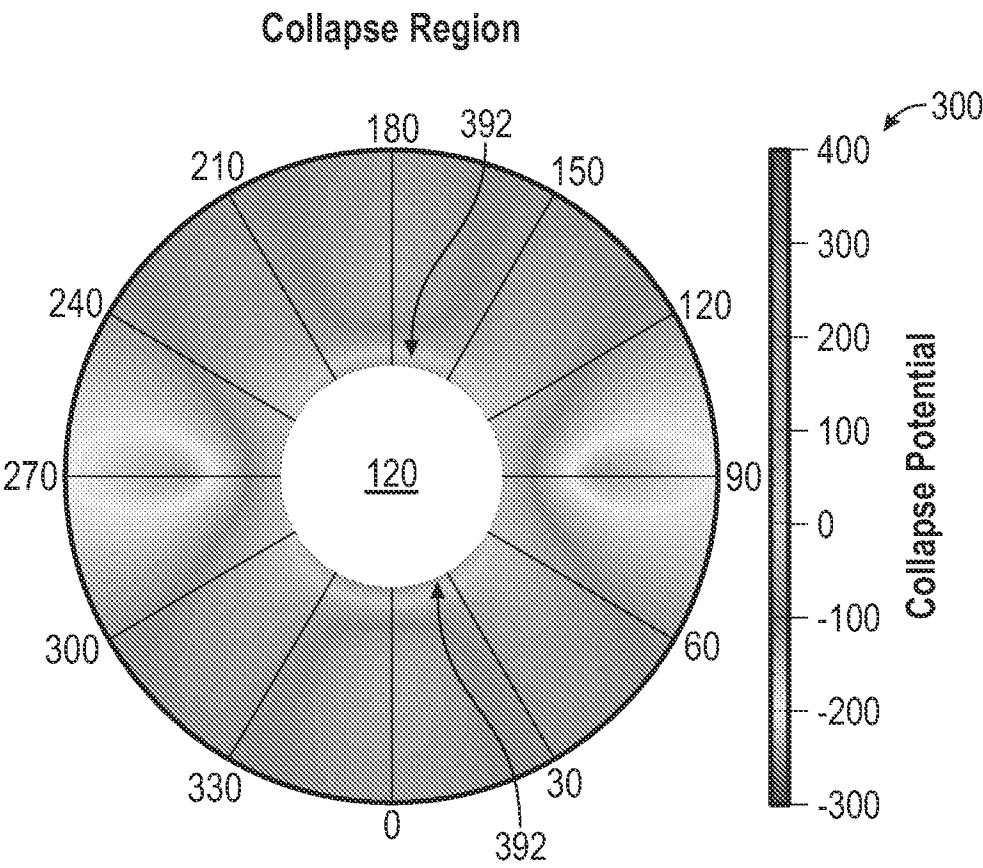


FIG. 3K

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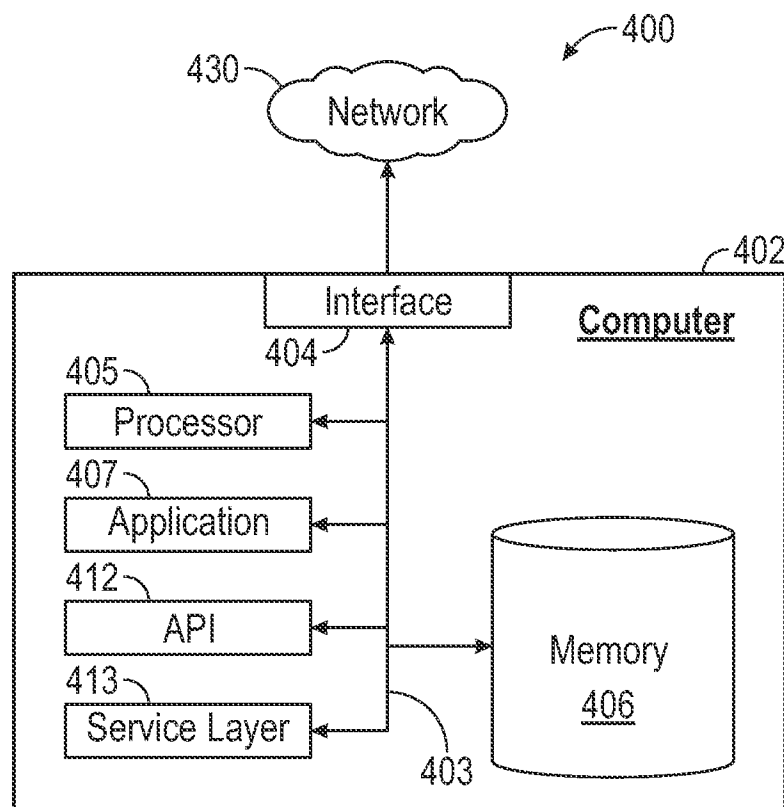


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/034468

A. CLASSIFICATION OF SUBJECT MATTER

INV. E21B21/08

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	HAN YANHUI ET AL: "An Integrative Software Platform to Support Drilling Operations in Troublesome Formations", ARAMCO AMERICAS: ARAMCO RESEARCH CENTER - HOUSTON, [Online] 7 March 2023 (2023-03-07), XP093208032, DOI: 10.2118/213695-MS Retrieved from the Internet: URL:https://watermark.silverchair.com/spe-213695-ms.pdf?token=AQECAHi208BE49Ooan9kKhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAA3MwggNvBgkqhkiG9w0BBwagggNgMIIDXAIBADCCA1UGCSqGSIB3DQEHATAeBgIghkgBZQMEAS4wEQQM8peeUDGKndeIej1VAgEQgIIDJiRwPMv14Saox2WM6c6gxRAeylg1Tq-lyy0AH5_U_zDH_0Xz_diNwfyOnn1CApCzvpeDEWlBDlCr9mpc6nIzS> [retrieved on 2024-09-24] abstract figures 1-3 - / - -	1 - 20



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

24 September 2024

Date of mailing of the international search report

07/10/2024

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Fax: (+31-70) 340-3016

Authorized officer

Hustedt, Bernhard

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2024/034468

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	SAGE-WSA; page 3, paragraph 3rd paragraph Analysis settings.; page 4, paragraph 2nd paragraph - page 5, paragraph 1st paragraph Formation properties.; page 5 Run.; page 5 -----	
Y	Yanhui Han ET AL: "Advanced Wellbore Stability Analysis for Drilling Naturally Fractured Rocks", , 18 March 2019 (2019-03-18), XP055616804, DOI: 10.2118/195021-MS Retrieved from the Internet: URL:https://onepetro.org/download/conferen ce-paper/SPE-195021-MS?id=conference-paper /SPE-195021-MS [retrieved on 2019-08-29] abstract Time-dependent stress model (poroelasticity); page 3 - page 4 -----	1-20
A	NWONODI ROLAND I ET AL: "An equivalent time-dependent analysis for predicting horizontal wellbore instability in a reactive shale formation using the imbibition/diffusion principle", GEOENERGY SCIENCE AND ENGINEERING, ELSEVIER, AMSTERDAM, NL, vol. 228, 20 June 2023 (2023-06-20), XP087358419, ISSN: 2949-8910, DOI: 10.1016/J.GEOEN.2023.212019 [retrieved on 2023-06-20] abstract 3 Materials and methods; page 5 4.2 The model for osmotic pressure; page 6 - page 7 5.1 Validation of the model; page 7 - page 8 ----- -/-	1,8,15

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2024/034468

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CUI L ET AL: "Poroelastic Solution for an Inclined Borehole", ASME JOURNAL OF APPLIED MECHANICS, [Online] vol. 64, 1 March 1997 (1997-03-01), pages 32-38, XP093208133, Retrieved from the Internet: URL:https://citeseerx.ist.psu.edu/document ?repid=rep1&type=pdf&doi=801e59c2f3e5ac785 72add26a090d9d0d3290eb6> [retrieved on 2024-09-24] abstract the whole document -----	1,8,15