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(54) DESIGN OF BOREHOLE COMPLETION PLAN BASED ON A FAILURE MODE OF ROCK

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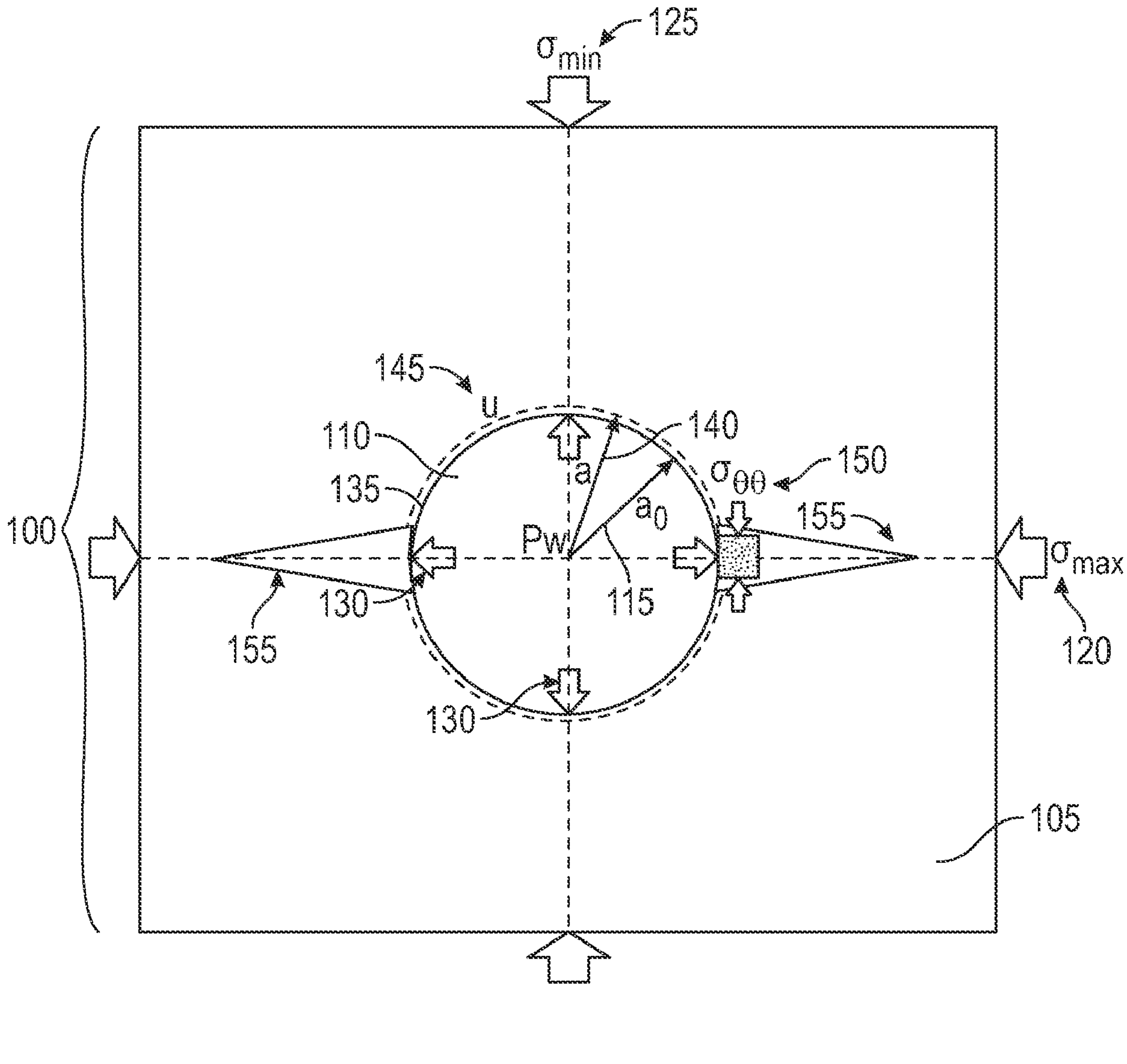
(57) ABSTRACT

Methods and systems are disclosed. Methods may include obtaining, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation and determining principal in-situ effective stresses and mechanical properties of the rock using the rock data. The methods may further include determining, using a first model, a breakdown pressure for the rock using the principal in-situ effective stresses and the mechanical properties and determining, using a second model, a yield pressure for the rock using the principal in-situ effective stresses and the mechanical properties. The methods may still further include determining a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure and designing, using a completion design system, a completion plan for the borehole based on the deformation mechanism, the failure mode, and the breakdown pressure.



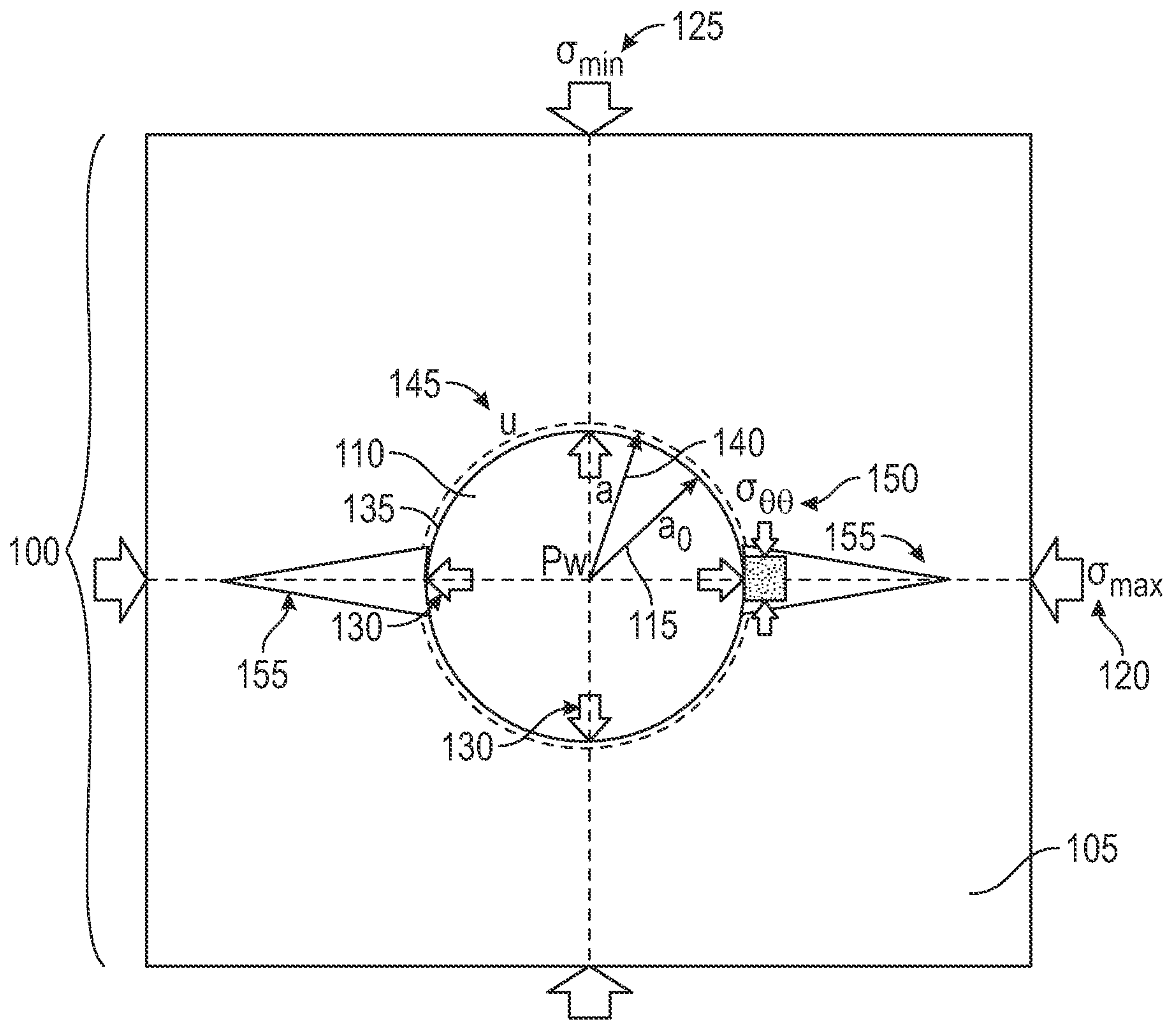

125
σ_{min}
145
u
110
140
150
$\sigma_{\theta\theta}$
135
a
a_0
155
100
Pw
σ_{max}
130
115
155
120
130
105

FIG. 1

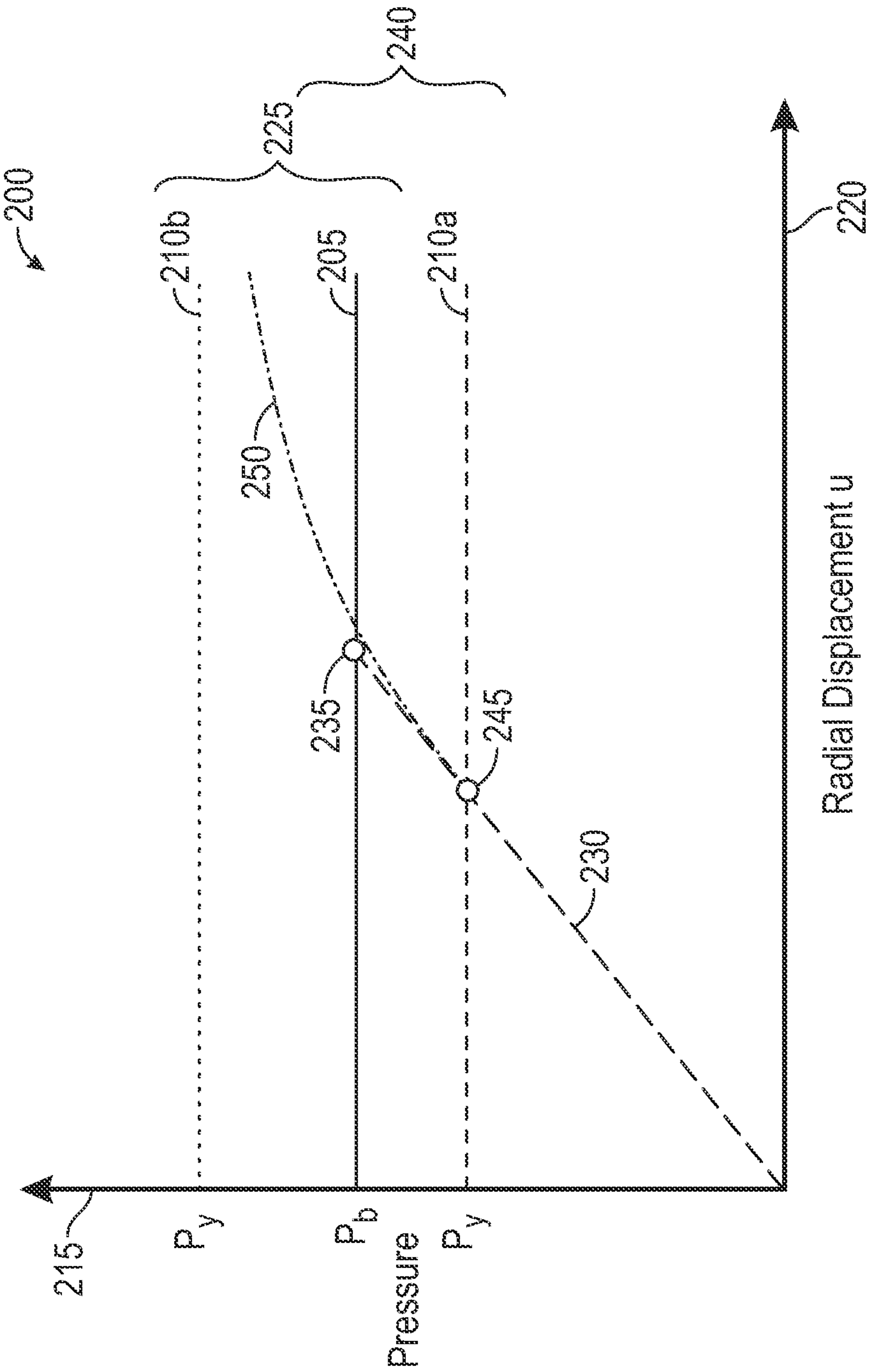

200
240
225
210b
205
210a
220
250
235
245
230
Radial Displacement u
215
P
y
P
b
P
y
Pressure

FIG. 2

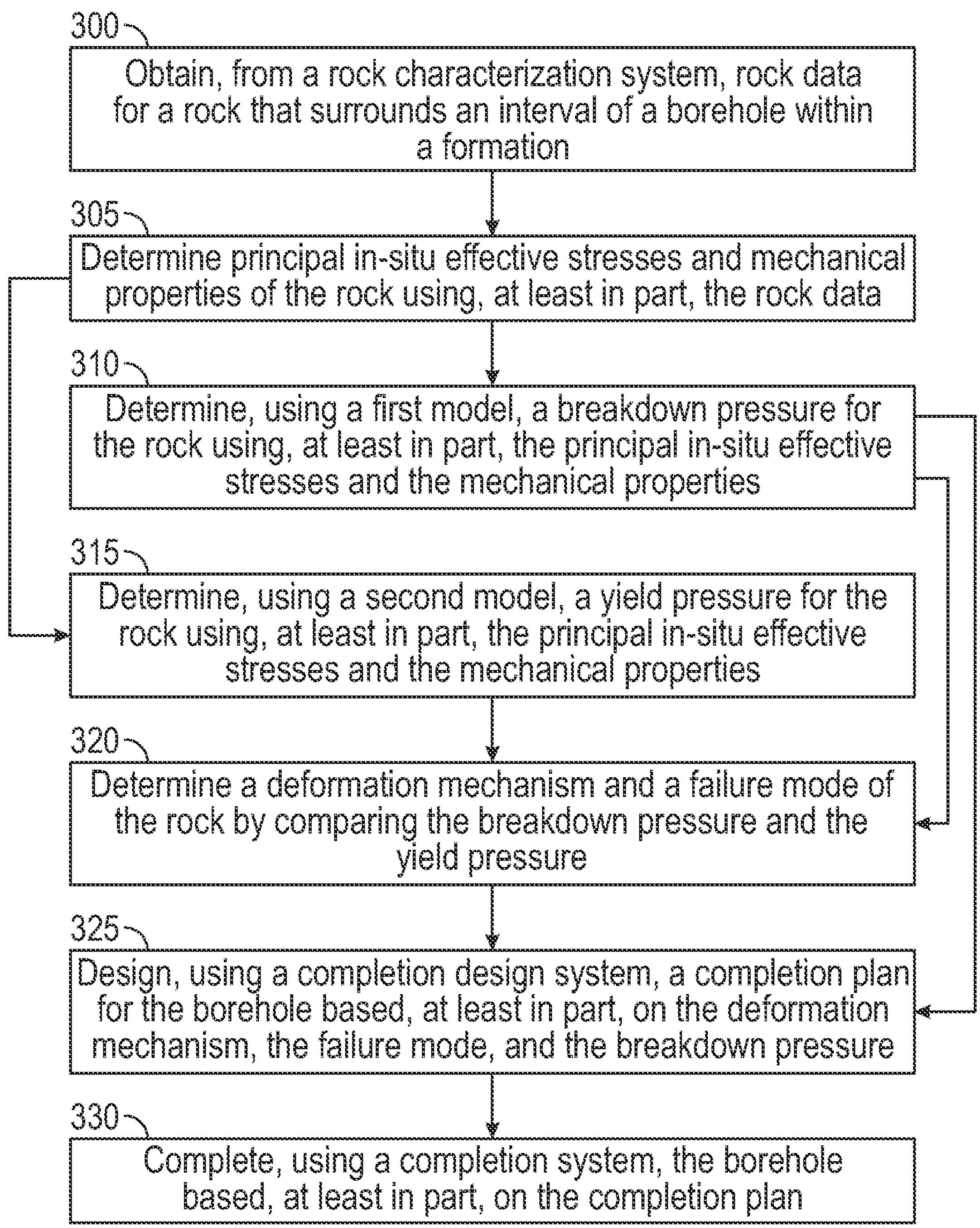

300
Obtain, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation
305
Determine principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data
310
Determine, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties
315
Determine, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties
320
Determine a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure
325
Design, using a completion design system, a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure
330
Complete, using a completion system, the borehole based, at least in part, on the completion plan

FIG. 3

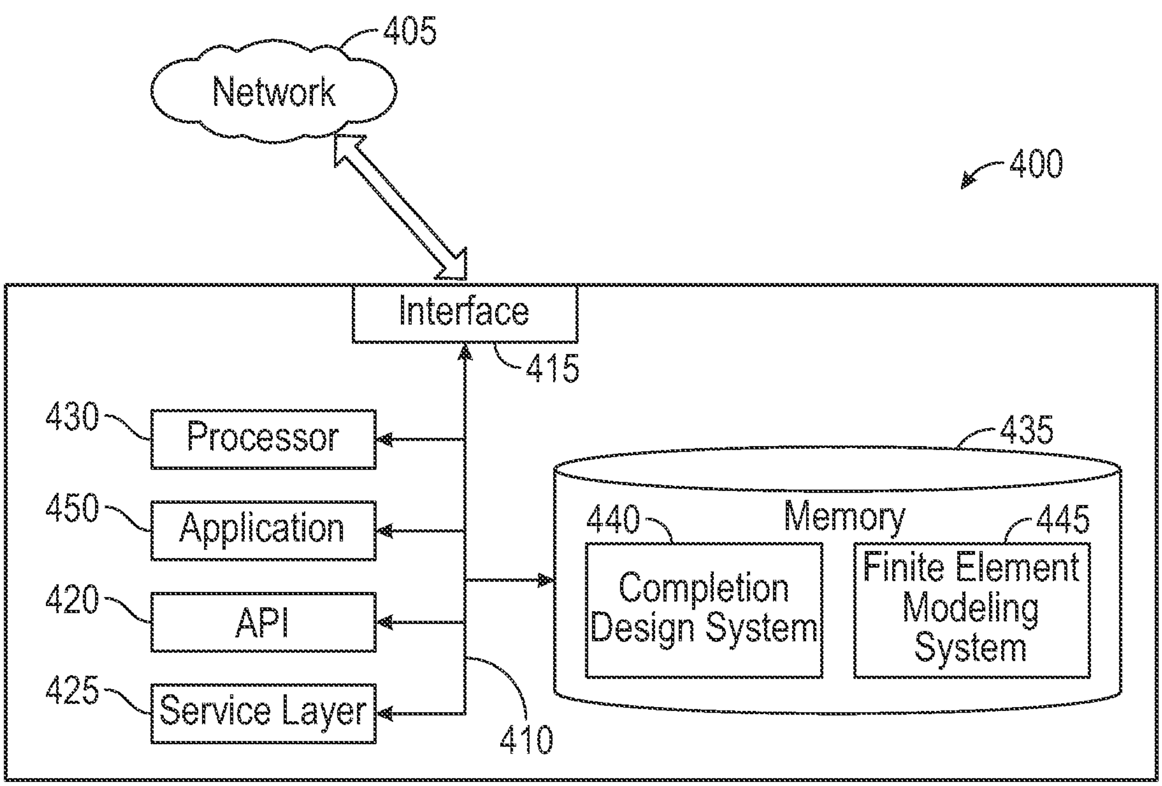

405
Network
400
Interface
415
430
Processor
450
Application
420
API
425
Service Layer
410
435
Memory
440
Completion Design System
445
Finite Element Modeling System

FIG. 4

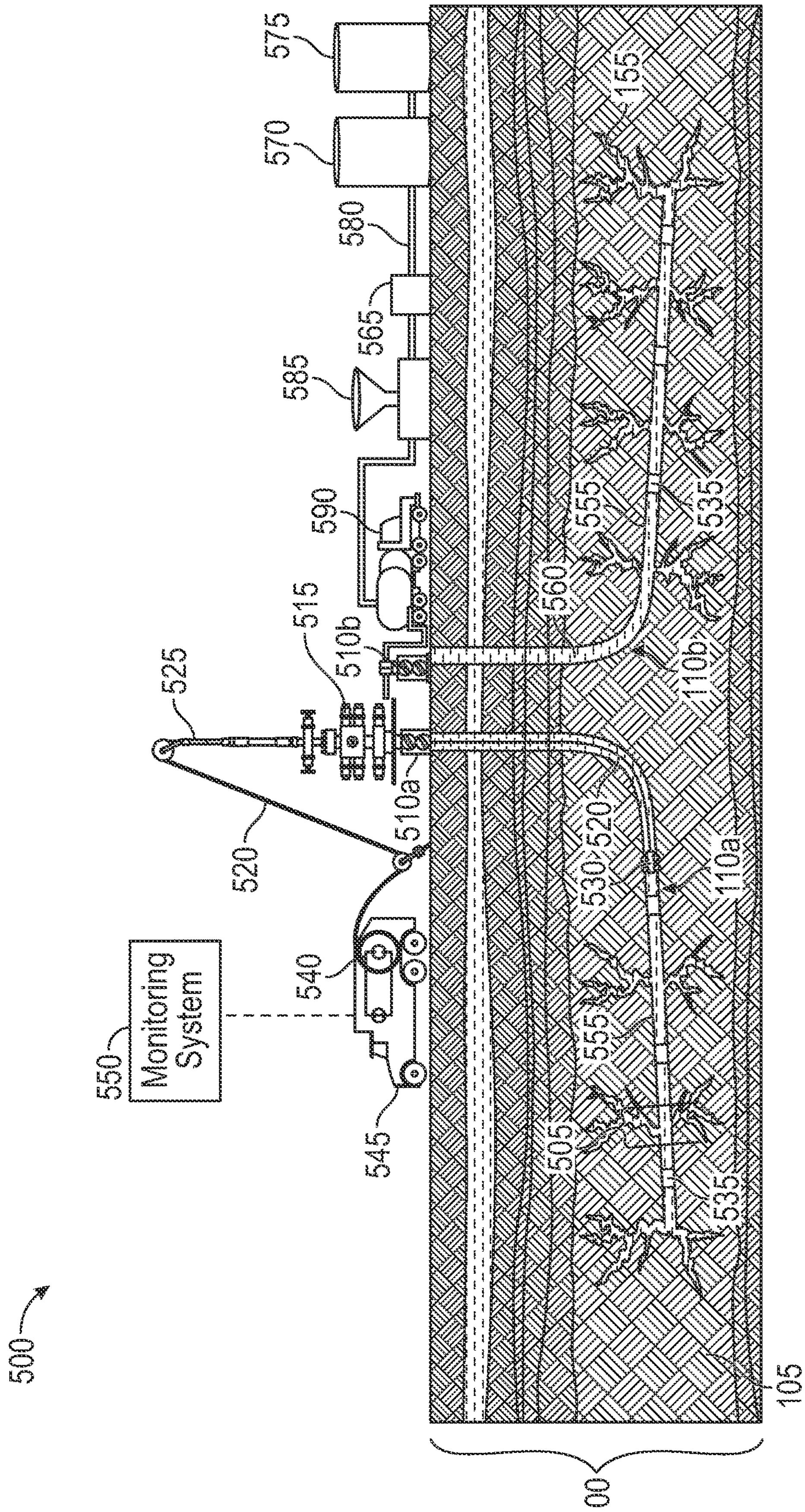

500
550
Monitoring System
540
545
520
525
515
510a
510b
590
585
565
580
570
575
560
555
535
155
505
530
110a
110b
105
100

FIG. 5

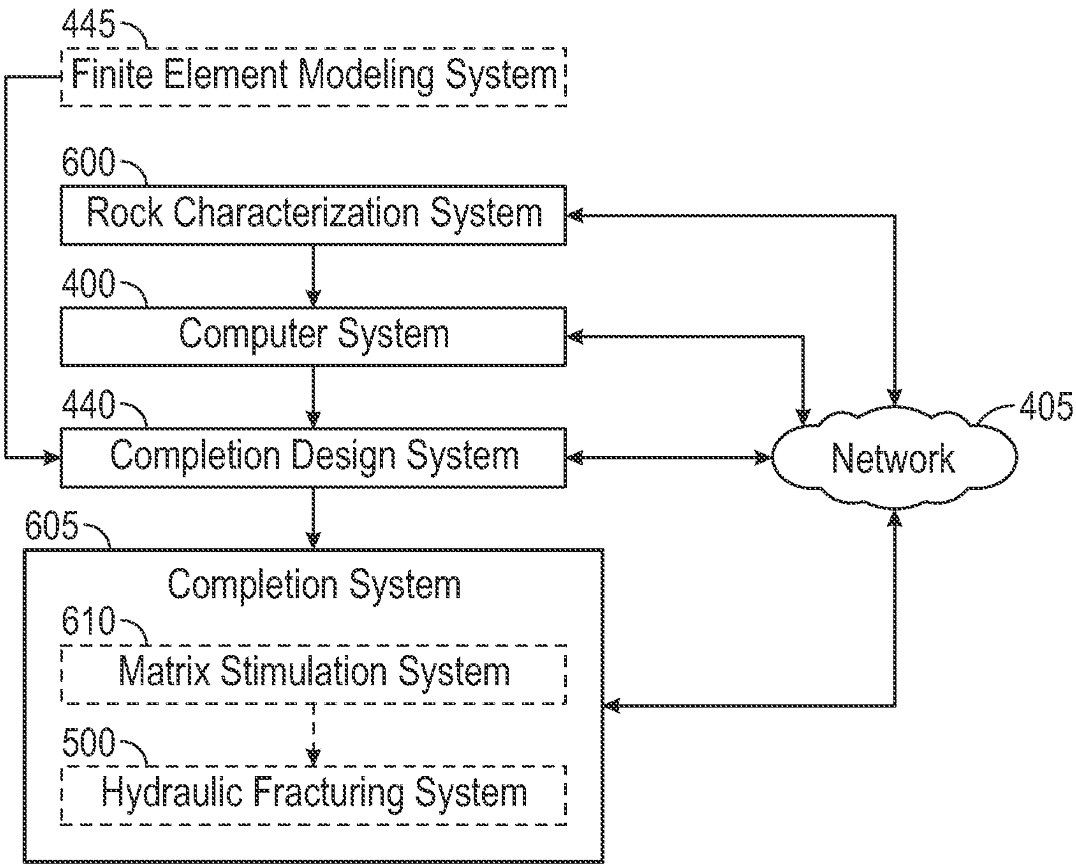

445
Finite Element Modeling System
600
Rock Characterization System
400
Computer System
440
Completion Design System
605
Completion System
610
Matrix Stimulation System
500
Hydraulic Fracturing System
Network
405

FIG. 6

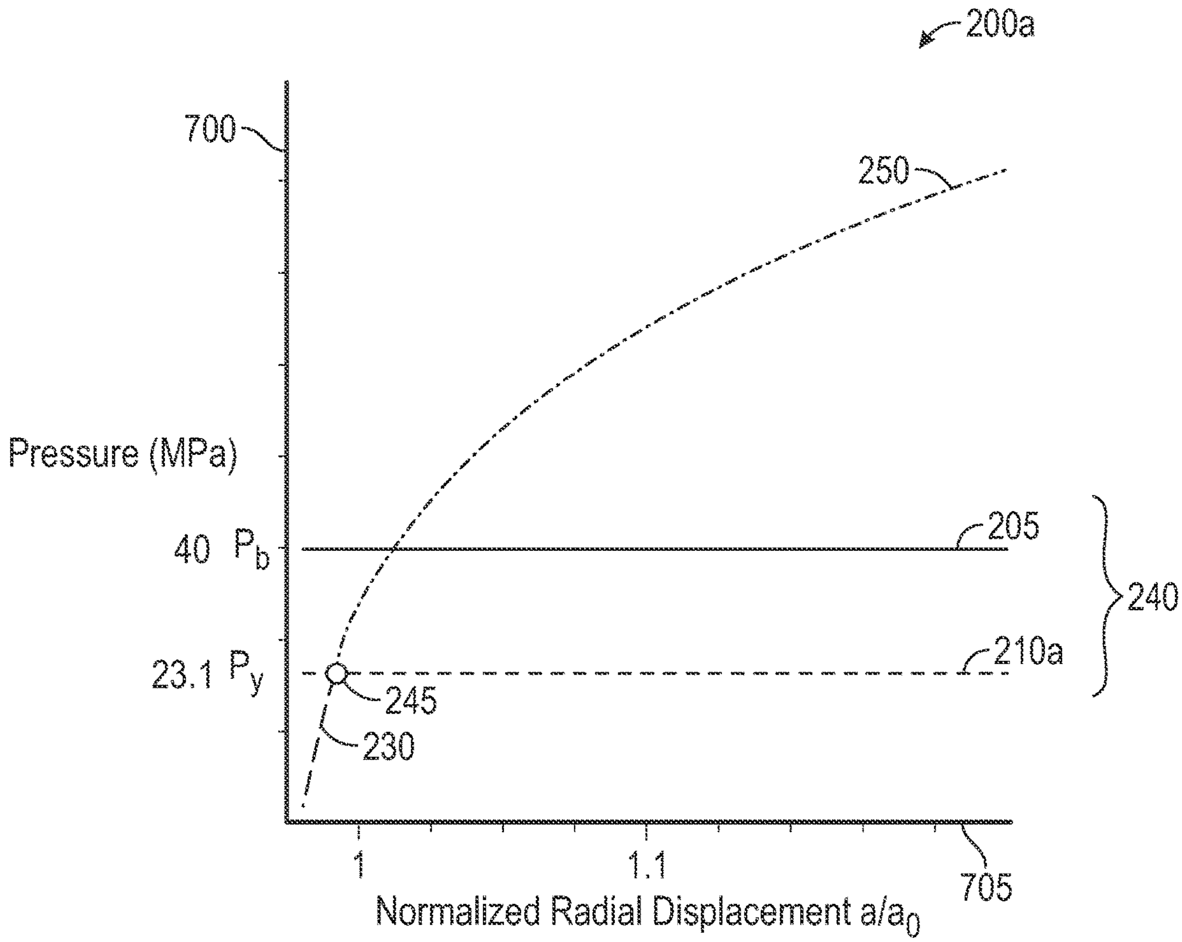

200a
700
250
Pressure (MPa)
40 P_b
205
240
23.1 P_y
210a
245
230
1
1.1
705
Normalized Radial Displacement a/a_0

FIG. 7

DESIGN OF BOREHOLE COMPLETION PLAN BASED ON A FAILURE MODE OF ROCK

BACKGROUND

[0001] Hydrocarbons may be stored in-situ within rock that forms an unconventional hydrocarbon reservoir. A hydraulic fracturing operation may be performed to induce fractures within the rock such that the stored hydrocarbons may be produced from the rock to the surface of the earth via a borehole. Typically, the hydraulic fracturing operation raises the pressure of a borehole fluid above a breakdown pressure to fracture the rock. However, the rock may fail to fracture above the breakdown pressure. Failure to fracture results in the loss of time and money. Further, failure to fracture results in the loss of production as hydrocarbons stored within the rock may not be produced from the rock unless fractured due to the low permeability of the rock.

SUMMARY

[0002] This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

[0003] In general, in one aspect, embodiments relate to a method. The method includes obtaining, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation and determining principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data. The method further includes determining, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties and determining, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties. The method further still includes determining a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure and designing, using a completion design system, a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure.

[0004] In general, in one aspect, embodiments relate to a system. The system includes a computer system and a completion design system. The computer system is configured to receive, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation and determine principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data. The computer system is further configured to determine, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties and determine, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties. The computer system is still further configured to determine a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure. The completion design system is configured to design a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure.

[0005] In general, in one aspect, embodiments relate to a non-transitory computer-readable memory having computer-executable instructions stored thereon that, when executed by a computer processor, perform steps. The steps include receiving, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation and determining principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data. The steps further include determining, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties and determining, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties. The steps further still include determining a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure and designing, using a completion design system, a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure.

[0006] Other aspects and advantages of the claimed subject matter 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] FIG. **1** illustrates a cross section of a formation in accordance with one or more embodiments.

[0009] FIG. **2** displays a pressure-displacement curve in accordance with one or more embodiments.

[0010] FIG. **3** describes a method in accordance with one or more embodiments.

[0011] FIG. **4** illustrates a computer system in accordance with one or more embodiments.

[0012] FIG. **5** illustrates a hydraulic fracturing operation in accordance with one or more embodiments.

[0013] FIG. **6** illustrates a flowchart of systems in accordance with one or more embodiments.

[0014] FIG. **7** displays an example pressure-displacement curve in accordance with one or more embodiments.

DETAILED DESCRIPTION

[0015] In the following detailed description of embodiments of the disclosure, numerous specific details are set forth 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.

[0016] 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.

[0017] It is to be understood that the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "a principal in-situ effective stress" includes reference to one or more of such stresses.

[0018] Terms such as "approximately," "substantially," etc., mean that the recited characteristic, parameter, or value need not be achieved exactly, but that deviations or variations, including for example, tolerances, measurement error, measurement accuracy limitations and other factors known to those of skill in the art, may occur in amounts that do not preclude the effect the characteristic was intended to provide.

[0019] It is to be understood that one or more of the steps shown in the flowcharts may be omitted, repeated, and/or performed in a different order than the order shown. Accordingly, the scope disclosed herein should not be considered limited to the specific arrangement of steps shown in the flowcharts.

[0020] Although multiple dependent claims are not introduced, it would be apparent to one of ordinary skill that the subject matter of the dependent claims of one or more embodiments may be combined with other dependent claims.

[0021] In the following description of FIGS. **1**-**7**, any component described regarding a figure, in various embodiments disclosed herein, may be equivalent to one or more like-named components described regarding any other figure. For brevity, descriptions of these components will not be repeated regarding each figure. Thus, each and every embodiment of the components of each figure is incorporated by reference and assumed to be optionally present within every other figure having one or more like-named components. Additionally, in accordance with various embodiments disclosed herein, any description of the components of a figure is to be interpreted as an optional embodiment which may be implemented in addition to, in conjunction with, or in place of the embodiments described regarding a corresponding like-named component in any other figure.

[0022] Methods and systems are disclosed to design a completion plan for a borehole. The term "completion" may describe the systems and/or operations used to bring the borehole into production or return the borehole to production. During production, hydrocarbons are produced from a hydrocarbon reservoir to the surface of the earth via the borehole that penetrates the hydrocarbon reservoir.

[0023] The term "openhole" may refer to the drilled-out portion of a formation that is uncased (i.e., casing is not installed downhole). The terms "borehole," "wellbore," and "well," which are often used interchangeably, may not indicate if casing is installed downhole. Hereinafter, the term "borehole" is adopted. The borehole may be completely drilled or partially drilled. The borehole may be uncased, partially cased, or cased. The borehole may or may not penetrate a hydrocarbon reservoir within the formation.

[0024] The hydrocarbon reservoir may be an unconventional hydrocarbon reservoir. The unconventional hydrocarbon reservoir may be made up of layers of rock, such as shale or mudstone, that store hydrocarbons within pores of the rock. Permeability is the measure of how easily fluids, such as the hydrocarbons, flow through the rock. Unconventional hydrocarbon reservoirs typically have extremely low permeability. As such, the hydrocarbons may be stationary or slowly flow through the rock.

[0025] Turning to FIG. **1**, FIG. **1** illustrates a cross section of a formation **100** in accordance with one or more embodiments. The cross section intersects rock **105** within the formation **100**. Further, the cross-section intersects an interval of a vertical borehole **110** previously drilled within the rock **105**. The borehole **110** is initially drilled to an initial radius a_0 **115**.

[0026] The rock **105** may be characterized by mechanical properties. The mechanical properties may include, but are not limited to friction angle, dilation angle, Biot's coefficient, Poisson's ratio, tensile strength, unconfined compressive strength, shear modulus, Young's modulus, and cohesion strength. Some mechanical properties may be specifically referred to as elastic properties and/or poroelastic properties. For example, Young's modulus may be an elastic property and Biot's coefficient may be a poroelastic property. Some mechanical properties are dependent on other mechanical properties. For example, the unconfined compressive strength may be dependent on cohesion strength and friction angle.

[0027] Further, the rock **105** may be subjected to principal in-situ effective stresses and pore pressure. The principal in-situ effective stresses confine the rock **105** and, as such, may be written in terms of confining stress. When represented in a cylindrical coordinate system, the principal in-situ effective stresses around the borehole **110** may be written in terms of radial stress and/or tangential stress.

[0028] Turning to the principal in-situ effective stresses, local rock **105** may experience three principal in-situ effective stresses each of which are orthogonal to a surface or face of the local rock **105**, where the local rock **105** may take any shape. FIG. **1** illustrates two horizontal principal in-situ effective stresses: a maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125**. A third principal in-situ effective stress (not shown) exists normal to the maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125**. The third principal in-situ effective stress may also be referred to as a vertical principal in-situ effective stress or overburden principal in-situ effective stress. The principal in-situ effective stresses may be compressive, anisotropic, and nonhomogeneous. Hereinafter, two or more of the maximum horizontal principal in-situ effective stress σ_{max} **120**, minimum horizontal principal in-situ effective stress σ_{min} **125**, and vertical principal in-situ effective stress are generically referred to as "principal in-situ effective stresses."

[0029] The magnitude of each principal in-situ effective stress may be controlled by other stresses and/or pressures. The other stresses and/or pressures may include, but are not limited to, the pore pressure P_p, surrounding stress, overburden stress, and injection pressure P_w **130**. The pore pressure P_p may be caused by fluid (e.g., the hydrocarbons) stored within the pores of the rock **105**. The surrounding stress and overburden stress may be caused by surrounding and overburden rock. The injection pressure P_w **130** may be caused by fluid injected into the rock **105** via the borehole

110. The injection pressure P_w **130** may place stress on the walls **135** of the borehole **110** as illustrated in FIG. **1**.

[0030] One or more of these other stresses and/or pressures may, in turn, cause the initial radius a_0 **115** of the borehole **110** to expand to expanded radius a **140**. The difference between the initial radius a_0 **115** and the expanded radius a **140** may be denoted radial displacement u **145**.

[0031] If the rock **105** is assumed to elastically deform, the maximum horizontal principal in-situ effective stress σ_{max} **120**, minimum horizontal principal in-situ effective stress σ_{min} **125**, and injection pressure P_w **130** may control a minimum tangential stress $\sigma_{\theta\theta}$ **150** located at the walls **135** of the borehole **110** based on the Kirsch solution where:

$$\sigma_{\theta\theta} = 3\sigma_{min} - \sigma_{max} - P_w. \qquad \text{Equation (1)}$$

[0032] The maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125** along with the tensile strength T of the rock **105** may control, at least in part, the pressure required to generate a fracture **155** within the rock **105** (i.e., fail the rock **105**). Hereinafter, the pressure required to generate a fracture **155** within the rock **105** is denoted breakdown pressure P_b. Further, hereinafter, the failure mode of the rock **105** following elastic deformation is denoted brittle fracture. The fracture **155** may propagate perpendicular to the minimum horizontal principal in situ stress σ_{min} **125** as illustrated in FIG. **1**. For example, if fluid is injected into the rock **105** via the borehole **110** at high pressures, the minimum tangential stress $\sigma_{74\ \theta}$ may become tensile and increase above the tensile strength T of the rock **105** and cause the rock **105** to fracture. The fracture **155** may occur at or near the breakdown pressure P_b where:

$$P_b = 3\sigma_{min} - \sigma_{max} + T. \qquad \text{Equation (2)}$$

Equation (2) is proposed by Hubbert and Willis and referred to as the H-W model. In the context of this disclosure, Equation (2) may be a first model or a modified version of Equation (2) may be the first model. For example, the breakdown pressure P_b may be considered a relative pressure above the pore pressure P_p and, as such, the true breakdown pressure P_b may be $P_b=3\ \sigma_{min}-\sigma_{max}+T+P_p$.

[0033] However, Equation (2) assumes the rock **105** elastically deforms and that the borehole **110** is impermeable. If the borehole **110** is assumed to elastically deform and be permeable, the rock **105** may fracture at or near:

$$P_b = \frac{3\sigma_{min} - \sigma_{max} + T}{2 - \beta\frac{1-2v}{1-v}}, \qquad \text{Equation (3)}$$

where β is Biot's coefficient and v is Poisson's ratio. Equation (3) is proposed by Haimson and Fairhurst and referred to as the H-F model. In the context of this disclosure, Equation (3) may be the first model or a modified version of Equation (3) may be the first model. For example, the breakdown pressure P_b may be considered a relative pressure above the pore pressure P_p and, as such, the true breakdown pressure P_b may be

$$P_b = \frac{3\sigma_{min} - \sigma_{max} + T}{2 - \beta\frac{1-2v}{1-v}} + P_p.$$

[0034] The elastic deformation of the rock **105** may be modeled using an elastic model. For example, if the rock **105** experiences isotropic confinement (i.e., $\sigma_{min}=\sigma_{max}=P_0$), the elastic model may take the form:

$$P_{elas} = 2G\frac{u}{a_0} + P_0, \qquad \text{Equation (4)}$$

where G is the shear modulus of the rock **105**. However, a person of ordinary skill in the art will appreciate that other elastic models may be used to model the elastic deformation of the rock **105** under isotropic confinement. Further, a person of ordinary skill in the art will appreciate that the rock **105** may experience anisotropic confinement (i.e., $\sigma_{min}\neq\sigma_{max}$) without departing from the scope of the disclosure.

[0035] Returning to Equations (2) and (3), neither consider that the rock **105** may plastically deform following elastic deformation and prior to fracture. If the rock **105** plastically deforms prior to fracture, the rock **105** may actually fracture well above the breakdown pressure P_b determined using Equation (2) or (3) or neighboring rock may fracture instead. Hereinafter, the failure mode of the rock **105** following plastic deformation is denoted ductile fracture.

[0036] The yield pressure P_y at the yield point where the rock **105** transitions from elastic deformation to plastic deformation may be determined using the Mohr-Coulomb failure criterion where:

$$P_y = \frac{UCS + N_\phi(3\sigma_{min} - \sigma_{max})}{N_\phi + 1}, \qquad \text{Equation (5)}$$

where

$$N_\phi = \frac{1+\sin\phi}{1-\sin\phi},$$

ϕ is the friction angle, and UCS is the unconfined compressive strength. In the context of this disclosure, Equation (5) may be a second model or a modified version of Equation (5) may be the second model.

[0037] The plastic deformation of the rock **105** may be modeled using a plastic model. For example, if the rock **105** experiences isotropic confinement, the plastic model may take the form:

$$P_{plas} = \frac{2N_\phi[UCS + (N_\phi - 1)P_0]}{(N_\phi + 1)(N_\phi - 1)}\left[\frac{1 - \left(\frac{a_0}{a}\right)^{1+\frac{1}{N_\psi}}}{1 - (1-\delta)^{1+\frac{1}{N_\psi}}}\right] - \frac{UCS}{(N_\phi - 1)}, \quad \text{Equation (6)}$$

where

$$N_\psi = \frac{1 + \sin\psi}{1 - \sin\psi},$$

ψ is dilation angle,

$$\gamma = \frac{N_\phi}{N_\psi}\frac{N_\psi + 1}{N_\phi - 1}, \text{ and } \delta = \frac{UCS + (N_\psi + 1)P_0}{2G(N_\phi - 1)}.$$

Equation (6) may be evaluated analytically to determine P_{plas}. However, a person of ordinary skill in the art will appreciate that other plastic models may be used to model the plastic deformation of the rock **105** under isotropic confinement. Further, a person of ordinary skill in the art will appreciate that the rock **105** may experience anisotropic confinement without departing from the scope of the disclosure. If the rock **105** experiences anisotropic confinement and both elastic deformation and plastic deformation, the elastic deformation and plastic deformation of the rock **105** may be numerically modeled using an elasto-plastic numerical model.

[0038] In some embodiments, the breakdown pressure P_b determined using Equation (2) or (3) and yield pressure P_y determined using Equation (5) may be compared to determine a deformation mechanism and failure mode of the rock **105**. The deformation mechanism includes elastic deformation and, in some embodiments, plastic deformation. The failure mode includes brittle failure and ductile failure. Prior to brittle failure, the rock **105** experiences elastic deformation. Prior to ductile failure, the rock experiences elastic deformation followed by plastic deformation. For illustration, FIG. **2** displays a pressure-displacement curve **200** in accordance with one or more embodiments. The pressure-displacement curve **200** may be used to visually compare the breakdown pressure P_b **205** and yield pressure P_y **210***a* and **210***b*. Pressure is displayed along the ordinate **215**. Radial displacement u **145** of the borehole **110** is displayed along the abscissa **220**.

[0039] The breakdown pressure P_b **205** is displayed as a horizontal line in FIG. **2**. Two values of the yield pressure P_y **210***a* and **210***b* are also displayed as horizontal lines in FIG. **2**. The first yield pressure P_y **210***a* is displayed below the breakdown pressure P_b **205**. The second yield pressure P_y **210***b* is displayed above the breakdown pressure P_b **205**.

[0040] If the breakdown pressure P_b **205** is less than or below the yield pressure P_y **210***b*, illustrated as configuration I **225** in FIG. **2**, the deformation mechanism and the failure mode of the rock **105** includes elastic deformation and brittle fracture, respectively. In some embodiments, the rock **105** elastically deforms based on the elastic model **230** of Equation (4) as illustrated in FIG. **2**. If configuration I **225** occurs, the rock **105** fractures at or near the fracture point **235** where the breakdown pressure P_b **205** and elastic model **230** intersect.

[0041] If the breakdown pressure P_b **205** is greater than or above the yield pressure P_y **210***a*, illustrated as configuration II **240** in FIG. **2**, the deformation mechanism and the failure mode of the rock **105** includes elastic deformation and plastic deformation and ductile fracture, respectively. In some embodiments, the rock **105** initially elastically deforms based on the elastic model **230** of Equation (4) and begins to plastically deform at the yield point **245** based on the plastic model **250** of Equation (6) as illustrated in FIG. **2**. In these embodiments, the rock **105** begins to plastically deform at the yield point **245** where the yield pressure P_y **210***a* and elastic model **230** intersect. The rock **105** may plastically deform due to the rock **105** experiencing shear stresses. If configuration II **240** occurs, the rock **105** may fracture well above the breakdown pressure P_b **205** or neighboring rock may fracture instead.

[0042] The deformation mechanism, failure mode, and breakdown pressure P_b **205** may be used, at least in part, to design a completion plan for the borehole **110**. The completion plan may be the plan designed to initially bring the borehole **110** into production or to return the borehole **110** to production.

[0043] FIG. **3** describes a method of designing a completion plan for a borehole **110** in accordance with one or more embodiments.

[0044] In step **300**, rock data is obtained for a rock **105**. The rock **105** surrounds an interval of a borehole **110** within a formation **100** as illustrated in FIG. **1**. In some embodiments, the rock **105** is a part of a hydrocarbon reservoir within the formation **100** that the borehole **110** may penetrate. The rock data is obtained from a rock characterization system. The rock characterization system may include at least one of a well logging system, hydraulic fracturing system, and rock core characterization system. In some embodiments, the well logging system is configured to obtain a density log, acoustic/sonic log, and/or caliper log (hereinafter, the rock data or a portion of the rock data) downhole within the borehole **110**. In other embodiments, the hydraulic fracturing system, as described in FIG. **5**, is configured to perform a minifrac test and/or leakoff test to obtain the rock data or a portion of the rock data. In still other embodiments, the rock core characterization system is configured to obtain the rock data or a portion of the rock data from rock cores within a laboratory setting. The rock core characterization system may be configured to perform mechanical tests (e.g., tensile tests, compression tests, shear tests, and/or failure tests), tilt tests, porosity tests, permeability tests, etc. to obtain the rock data or a portion of the rock data.

[0045] In step **305**, mechanical properties of the rock **105** are determined. The mechanical properties are determined directly or indirectly from the rock data obtained in step **300**. In some embodiments, the mechanical properties include friction angle, tensile strength, and unconfined compressive strength. In other embodiments, the mechanical properties additionally include Biot's coefficient and Poisson's ratio.

[0046] In some embodiments, such as when the borehole **110** within the interval is vertical, the principal in-situ effective stresses may include the maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125** as illustrated in FIG. **1**. In other embodiments, such as when the borehole **110** within the interval is lateral, the principal in-situ effective stresses may include the vertical principal in-situ effective stress and a horizontal principal in-situ effective stress. In some embodiments, the vertical principal in-situ effective stress may be determined by integration of a density log. In some embodiments, the maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125** may be determined from the rock data obtained from the minifrac test and/or leakoff test. In other embodiments, the maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125** may be determined from the sonic log. In still other embodiments, the maximum horizontal principal in-situ effective stress σ_{max} **120** may be inversely determined from the caliper log.

[0047] In some embodiments, the rock data determined from the tilt test may be used to determine the friction angle. In some embodiments, the tensile strength may be determined from the rock data obtained from the minifrac test or a tensile-to-failure test. In some embodiments, the unconfined compressive strength may be determined from the rock data obtained from the compressive test.

[0048] However, a person of ordinary skill in the art will appreciate that the above embodiments are not meant to be an exhaustive list of systems, tests, and methods used to determine the mechanical properties of the rock **105** but are offered as nonlimiting examples only. Any rock characterization system, whether used downhole or in a laboratory setting, any test, and any method may be used to determine the mechanical properties of the rock **105** without departing from the scope of the disclosure.

[0049] In step **310**, the breakdown pressure P_b **205** is determined for the rock **105**. To do so, a first model is relied on along with the principal in-situ effective stresses and tensile strength determined in step **305**. If the borehole **110** is assumed to be impermeable, Equation (2) may be the first model. In these embodiments, the principal in-situ effective stresses σ_{max} and σ_{min} and tensile strength T are input into the first model of Equation (2) to determine the breakdown pressure P_b **205**. If the borehole **110** is assumed to be permeable, Equation (3) may be the first model. In these embodiments, the principal in-situ effective stresses σ_{max} and σ_{min}, tensile strength T, Biot's coefficient, and Poisson's ratio are input into the first model of Equation (3) to determine the breakdown pressure P_b **205**. However, a person of ordinary skill in the art will appreciate that the first model may be any model that may be used to determine the breakdown pressure P_b **205** of the rock **105** that assumes that the rock **105** elastically deforms.

[0050] In step **315**, the yield pressure P_y **210***a* and **210***b* is determined for the rock **105**. To do so, a second model is relied on along with the principal in-situ effective stresses, friction angle, and unconfined compressive strength determined in step **305**. In some embodiments, Equation (5) may be the second model. In these embodiments, the principal in-situ effective stresses σ_{max} and σ_{min}, friction angle, and unconfined compressive strength are input into the second model of Equation (5) to determine the yield pressure P_y **210***a* and **210***b*. However, a person of ordinary skill in the art will appreciate that the second model may be any model that determines the yield pressure P_y **210***a* and **210***b* of the rock **105**.

[0051] In step **320**, a deformation mechanism and failure mode of the rock **105** are determined. The deformation mechanism and failure mode are determined by comparing the breakdown pressure P_b **205** determined in step **310** and the yield pressure P_y **210***a* and **210***b* determined in step **315**. If the breakdown pressure P_b **205** is less than or below the yield pressure P_y **210***b*, illustrated as configuration I **225** in FIG. **2**, the deformation mechanism and failure mode of the rock **105** includes elastic deformation and brittle failure, respectively. If configuration I **225** occurs, the rock **105** fractures at or near the breakdown pressure P_b **205** at the fracture point **235** following elastic deformation. If the breakdown pressure P_b **205** is greater than or above the yield pressure P_y **210***a*, illustrated as configuration II **240** in FIG. **2**, the deformation mechanism and failure mode of the rock **105** includes elastic deformation followed by plastic deformation and ductile failure, respectively. If configuration II **240** occurs, the rock **105** may fracture well above the breakdown pressure P_b **205** or neighboring rock may fracture instead following plastic deformation.

[0052] In step **325**, a completion plan is designed for the borehole **110**. The completion plan may be designed based, at least in part, on the deformation mechanism and failure mode determined in step **320** and the breakdown pressure P_b **205** determined in step **310**. Details regarding what may be included within the completion plan are described below following a discussion of completion operations and completion systems.

[0053] If configuration I **225** occurs, designing the completion plan may include designing a matrix stimulation operation below the breakdown pressure P_b **205** and/or designing a hydraulic fracturing operation above the breakdown pressure P_b **205**.

[0054] If configuration II **240** occurs, designing the completion plan may include generating a finite element model of the rock **105** that surrounds the interval of the borehole **110** within the formation **100**. The finite element model may model or simulate the stress state (i.e., stress field) of the rock **105** over time as fluid is injected into the rock **105** via the borehole **110**. In some embodiments, the finite element model may take the form of a finite element model, finite difference model, or finite volume model. The finite element model may include the elastic model **230**, plastic model **250**, and yield pressure Y_p **210***a* and **210***b* as well as other structural/geometrical, mechanical, boundary condition, and/or mesh information. A person of ordinary skill in the art will appreciate that the combination of the elastic model **230** and plastic model **250** may be referred to as an elastoplastic model. In some embodiments, a finite element modeling system may be configured to generate the finite element model. The finite element modeling system may take the form of software located on a memory of a computer system.

[0055] In some embodiments, the finite element model may be used to determine an updated breakdown pressure P_b that reflects the true breakdown pressure P_b that causes the rock **105** to fracture following plastic deformation. In these embodiments, designing the completion plan may include designing a matrix stimulation operation below the updated breakdown pressure P_b and/or designing a hydraulic fracturing operation above the updated breakdown pressure P_b.

[0056] In other embodiments, the finite element model may be used to determine that the rock **105** does not fracture at a breakdown pressure P_b that can reasonably be applied to the rock **105**. In these embodiments, designing the completion plan may include designing a matrix stimulation operation or not completing the borehole **110** along the interval. In these embodiments, designing the completion plan may exclude designing a hydraulic fracturing operation as the finite element model has determined that the rock **105** may not fracture at a breakdown pressure P_b that can reasonably be applied to the rock **105**.

[0057] In still other embodiments, the finite element model may determine that surrounding rock fractures instead. In these embodiments, designing the completion plan may include designing a matrix stimulation operation below the updated breakdown pressure P_b for the surrounding rock and/or designing a hydraulic fracturing operation above the updated breakdown pressure P_b for the surrounding rock.

[0058] In some embodiments, a completion design system may be configured to design the completion plan. The completion design system may take the form of software located on the memory of the computer system.

[0059] In step **330**, in some embodiments, the borehole **110** may be completed based, at least in part, on the completion plan designed in step **325**. The borehole **110** may be completed using a completion system. If the completion plan includes a matrix stimulation operation, the completion system may include a matrix stimulation system. If the completion plan includes a hydraulic fracturing operation, the completion system may include a hydraulic fracturing system.

[0060] FIG. **4** illustrates a computer system **400** in accordance with one or more embodiments. The computer system **400** may be used to provide computational functionalities associated with described algorithms, methods, functions, processes, flows, and procedures as described in this disclosure, according to one or more embodiments. The illustrated computer system **400** 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 system **400** 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 system **400**, including digital data, visual, or audio information (or a combination of information), or a GUI.

[0061] The computer system **400** 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 system **400** is communicably coupled with a network **405**. In some implementations, one or more components of the computer system **400** may be configured to operate within environments, including cloud-computing-based, local, global, or other environment (or a combination of environments).

[0062] At a high level, the computer system **400** 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 system **400** 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).

[0063] The computer system **400** can receive requests over network **405** from a client application (for example, executing on another computer system **400**) 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 system **400** 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 computer systems.

[0064] Each of the components of the computer system **400** can communicate using a system bus **410**. In some implementations, any or all of the components of the computer system **400**, both hardware or software (or a combination of hardware and software), may interface with each other or the interface **415** (or a combination of both) over the system bus **410** using an application programming interface (API) **420** or a service layer **425** (or a combination of the API **420** and service layer **425**. The API **420** may include specifications for routines, data structures, and object classes. The API **420** 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 **425** provides software services to the computer system **400** or other components (whether or not illustrated) that are communicably coupled to the computer system **400**. The functionality of the computer system **400** may be accessible for all service consumers using this service layer. Software services, such as those provided by the service layer **425**, 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 system **400**, alternative implementations may illustrate the API **420** or the service layer **425** as stand-alone components in relation to other components of the computer system **400** or other components (whether or not illustrated) that are communicably coupled to the computer system **400**. Moreover, any or all parts of the API **420** or the service layer **425** 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.

[0065] The computer system **400** includes an interface **415**. Although illustrated as a single interface **415** in FIG. **4**, two or more interfaces **415** may be used according to particular needs, desires, or particular implementations of the computer system **400**. The interface **415** is used by the computer system **400** for communicating with other systems in a distributed environment that are connected to the network **405**. Generally, the interface **415** includes logic encoded in software or hardware (or a combination of software and hardware) and operable to communicate with the network **405**. More specifically, the interface **415** may include software supporting one or more communication protocols associated with communications such that the network **405** or interface's hardware is operable to communicate physical signals within and outside of the illustrated computer system **400**.

[0066] The computer system **400** includes at least one computer processor **430**. Although illustrated as a single computer processor **430** in FIG. **4**, two or more processors may be used according to particular needs, desires, or particular implementations of the computer system **400**. Generally, the computer processor **430** executes instructions and manipulates data to perform the operations of the computer system **400** and any algorithms, methods, functions, processes, flows, and procedures as described in the instant disclosure.

[0067] The computer system **400** also includes a memory **435** that stores software and data. In some embodiments, the memory **435** may store a completion design system **440** that may be configured to perform step **325** as previously described relative to FIG. **3**. In some embodiments, the memory **435** may store a finite element modeling system **445**. Although illustrated as a single memory **435** in FIG. **4**, two or more memories **435** may be used according to particular needs, desires, or particular implementations of the computer system **400** and the described functionality. While memory **435** is illustrated as an integral component of the computer system **400**, in alternative implementations, memory **435** can be external to the computer system **400**.

[0068] The application **450** is an algorithmic software engine providing functionality according to particular needs, desires, or particular implementations of the computer system **400**, particularly with respect to functionality described in this disclosure. For example, application **450** can serve as one or more components, modules, applications, etc. Further, although illustrated as a single application **450**, the application **450** may be implemented as multiple applications **450** on the computer system **400**. In addition, although illustrated as integral to the computer system **400**, in alternative implementations, the application **450** can be external to the computer system **400**.

[0069] There may be any number of computer systems **400** associated with, or external to, a computer system containing a computer system **400**, wherein each computer system **400** communicates over network **405**. 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 system **400**, or that one user may use multiple computer systems **400**.

[0070] Following the design of the completion plan using the completion design system **440**, the borehole **110** may be completed based on the completion plan. In some embodiments, completing the borehole **110** may include performing a matrix simulation operation within the rock **105** surrounding the interval of the borehole **110** or surrounding rock. In other embodiments, completing the borehole **110** may additionally or alternatively include performing a hydraulic fracturing operation within the rock **105** surrounding the interval of the borehole **110** or surrounding rock. In still other embodiments, completing the borehole **110** may include not completing the rock **105** surrounding the interval of the borehole **110**.

[0071] The matrix stimulation operation (hereinafter "matrix stimulation") is also known as a matrix treatment or matrix acidizing. Matrix stimulation is a treatment to increase the permeability of rock **105** within a hydrocarbon reservoir and, in turn, increase production. A matrix stimulation system may be configured to perform matrix stimulation. During matrix stimulation, a treatment fluid may be injected into the rock **105** via the borehole **110** at pressures below the breakdown pressure P_b **205** or updated breakdown pressure P_b. The treatment fluid may include, but is not limited to, an acid (e.g., hydrochloric acid, formic acid, and acetic acid), solvent, or other chemical.

[0072] If the hydrocarbon reservoir includes sandstone, matrix stimulation may restore or increase the permeability of the rock **105** within the formation **100** by removing debris from the formation **100**, dissolving other material plugging the pores of the rock **105**, or enlarging the pores of the rock **105**. As such, information regarding the extent, type of formation debris, location, origin, reservoir mineralogy, and compatibility of the treatment fluid within the formation **100** may be additionally considered to design a completion plan that includes a matrix stimulation operation. To perform a matrix simulation operation in sandstone, for example, rock **105** may be preflushed with a hydrochloric acid, treated with a main treating fluid, and overflushed with a weak acid solution or brine. The main treating fluid is maintained under pressure inside the hydrocarbon reservoir for a period of time, after which the borehole **110** is swabbed and enters or is returned to production.

[0073] If the hydrocarbon reservoir includes carbonate, matrix stimulation generates new, highly conductive channels (i.e., wormholes) that bypass debris within the formation **100**. As such, information regarding the temperature of the hydrocarbon reservoir, pumping rate, and fluid type may be additionally considered to design a completion plan that includes a matrix stimulation operation as each may affect the reactivity of the main treating fluid with the rock **105**.

[0074] As such, if matrix stimulation is performed, the completion plan may include the goals of the completion plan, the fluid used for each of the preflush, treatment, and overflush, the location within the rock **105** that matrix stimulation will be performed on, the pressure of the main treating fluid downhole, and how long the main treating fluid will be downhole.

[0075] The hydraulic fracturing operation (hereinafter also "hydraulic fracturing") is also known as "hydraulic stimulation" or colloquially "frac job." FIG. **5** illustrates a hydraulic fracturing operation in accordance with one or more embodiments. The hydraulic fracturing operation and hydraulic fracturing system **500** are for illustration purposes only. The scope of the disclosure is intended to encompass any type of hydraulic fracturing operation and hydraulic fracturing system **500**. In some embodiments, the completion design system **440** may transfer information associated with the completion plan to the hydraulic fracturing system **500** via the network **405** such that the hydraulic fracturing system **500** may perform the hydraulic fracturing operation at the location of the interval **505**.

[0076] In some embodiments, the hydraulic fracturing operation is performed by separating the borehole **110** into multiple packed borehole lengths and fracturing each interval **505** in "stages." Further, the hydraulic fracturing operation may be performed on multiple boreholes **110** that are geographically grouped. A single borehole **110** may have anywhere from one to more than forty stages. Typically, each stage includes one perforation operation and one pumping operation. While one operation is occurring on one borehole **110**, a second operation may be performed on the other borehole **110**. As such, FIG. **5** shows a hydraulic fracturing operation occurring on a first borehole **110***a* and a second borehole **110***b*. The first borehole **110***a* is undergoing the perforation operation and the second borehole **110***b* is undergoing the pumping operation.

[0077] The boreholes **110***a* and **110***b* are horizontal in that each borehole **110***a* and **110***b* includes a vertical section and a lateral section. The lateral section is a section of the borehole **110***a* and **110***b* that is drilled at least eighty degrees from vertical. The first borehole **110***a* is capped by a first frac tree **510***a* and the second borehole **110***b* is capped by a second frac tree **510***b*. Those of ordinary skill in the art will appreciate that the use of the term "frac" refers to "fracturing" and is used herein to describe elements that may be used in a hydraulic fracturing operation. Each frac tree **510***a* and **510***b* is similar to a Christmas/production tree but is specifically installed for the hydraulic fracturing operation. The frac trees **510***a* and **510***b* tend to have larger bores and higher-pressure ratings than a Christmas/production tree would have. Further, hydraulic fracturing operations require abrasive materials being pumped into the boreholes **110***a* and **110***b* at high pressures, so each frac tree **510***a* and **510***b* is designed to handle a higher rate of erosion.

[0078] In some embodiments, each borehole **110***a* and **110***b* requires four stages. Both the first borehole **110***a* and the second borehole **110***b* have undergone three stages and are undergoing the fourth stage. The second borehole **110***b* has already undergone the fourth stage perforation operation and is currently undergoing the fourth stage pumping operation. The first borehole **110***a* is undergoing the fourth stage perforating operation and has yet to undergo the fourth stage pumping operation.

[0079] In some embodiments, the perforating operation includes installing a wireline blow out preventor (BOP) **515** onto the first frac tree **510***a*. A wireline BOP **515** is similar to a drilling BOP. However, a wireline BOP **515** has seals designed to close around (or shear) wireline **520** rather than drill pipe. A lubricator **525** is connected to the opposite end of the wireline BOP **515**. A lubricator **525** is a long, high-pressure pipe used to equalize between downhole pressure and atmosphere pressure to run downhole tools, such as a perforating gun **530**, into the first borehole **110***a*.

[0080] The perforating gun **530** is pumped into the first borehole **110***a* using the lubricator **525**, wireline **520**, and fluid pressure. In accordance with one or more embodiments, the perforating gun **530** is equipped with explosives and a frac plug **535** prior to being deployed in the first borehole **110***a*. The wireline **520** is connected to a spool **540** often located on a wireline truck **545**. Electronics (not pictured) included in the wireline truck **545** are used to control the unspooling/spooling of the wireline **520** and are used to send and receive messages along the wireline **520**. The electronics may also be connected, wired or wirelessly, to a monitoring system **550** that is used to monitor and control the various operations being performed by the hydraulic fracturing system **500**.

[0081] When the perforating gun **530** reaches a predetermined depth, a message is sent along the wireline **520** to set the frac plug **535**. After the frac plug **535** is set, another message is sent through the wireline **520** to detonate the explosives, as shown in FIG. **5**. The explosives create perforations in the casing **555** and in the surrounding formation **100**. There may be more than one set of explosives on a singular perforating gun **530**, each detonated by a distinct message. Multiple sets of explosives are used to perforate different depths along the casing **555** for a singular stage. Further, the frac plug **535** may be set separately from the perforation operation without departing from the scope of the disclosure herein.

[0082] As explained above, FIG. **5** shows the second borehole **110***b* undergoing the pumping operation after the fourth stage perforating operation has already been performed and perforations are left behind in the casing **555** and the surrounding formation **100**. A pumping operation includes pumping a frac fluid **560** into the perforations to propagate the perforations and create fractures **155** in the surrounding formation **100**. The frac fluid **560** often includes a certain percentage of water, proppant, and chemicals.

[0083] FIG. **5** further shows chemical storage containers **565**, water storage containers **570**, and proppant storage containers **575** that are constituents of the hydraulic fracturing system **500**. Frac lines **580** and transport belts (not pictured) transport the chemicals, proppant, and water from the storage containers **565**, **570**, **575** into a frac blender **585**. Sensors (not pictured) are located throughout this equipment to send signals to the monitoring system **550**. The monitoring system **550** may be used to control the volume of water, chemicals, and proppant used in the pumping operation.

[0084] The frac blender **585** blends the water, chemicals, and proppant to become the frac fluid **560**. The frac fluid **560** is transported to one or more frac pumps, often pump trucks **590**, to be pumped through the second frac tree **510***b* into the second borehole **110***b*. Each pump truck **590** includes a pump designed to pump the frac fluid **560** at a certain pressure. More than one pump truck **590** may be used at a time to increase the pressure of the frac fluid **560** being pumped into the second borehole **110***b*. The frac fluid **560** is transported from the pump truck **590** to the second frac tree **510***b* using frac lines **580**.

[0085] The fluid pressure propagates and creates the fractures **155** while the proppant props open the fractures **155** once the pressure is released. Different chemicals may be used to lower friction pressure, prevent corrosion, etc. The pumping operation may be designed to last a certain length of time to ensure the fractures **155** have sufficiently propagated. Further, the frac fluid **560** may have different make ups throughout the pumping operation to optimize the pumping operation without departing from the scope of the disclosure herein.

[0086] When the hydraulic fracturing operation is completed on either borehole **110***a* and **110***b*, the frac trees **510***a* and **510***b* must be removed from each borehole **110***a* and **110***b* to perform the final completion operations which include drilling out the plugs **535** using coiled tubing or a snubbing unit and installing production tubing (not pictured). The production tubing is installed by running the length of production tubing into each borehole **110***a* and **110***b* and landing out the tubing hanger (i.e., the surface extending portion of the production tubing that has seals) into a tubing head that caps each borehole **110***a* and **110***b*.

[0087] As such, if hydraulic fracturing is performed, the completion plan may include the number of stages that will be performed on the borehole **110**, the length of each interval **505**, when, where, and for how long each perforation operation and pumping operation will be performed, what and when frac fluids **560** and proppant are pumped into the borehole **110**, what sets of explosives are used for each perforation operation, and what final completion operations will be used.

[0088] FIG. **6** illustrates a flowchart of systems in accordance with one or more embodiments. Systems within a dashed-line box may be optional. The rock characterization system **600** may be configured to obtain the rock data from the rock **105**. The rock characterization system **600** may include at least one of a well logging system, hydraulic fracturing system **500**, and rock core characterization system. The rock data may be transferred to and stored on the computer system **400** via the network **405**. The computer system **400** may be configured to perform steps **300**, **305**, **310**, **315**, and **320**. A completion design system **440** may be configured to perform step **325**. In some embodiments, a finite element modeling system **445** may be configured to design the completion plan. For example, the finite element modeling system **445** may be configured to generate the finite element model and determine an updated breakdown pressure if configuration II **240** occurs.

[0089] Following the design of the completion plan, the completion plan may be transferred to and stored on the completion system **605** via the network **405**. The completion system **605** may be configured to complete the borehole **110** based, at least in part, on the completion plan. If configuration I **225** occurs, the completion system **605** may include a matrix stimulation system **610** and/or hydraulic fracturing system **500**. The matrix stimulation system **610** may be configured to perform a matrix stimulation operation on the rock **105** surrounding the interval **505** of the borehole **110** or surrounding rock. The hydraulic fracturing system **500** may be configured to perform a hydraulic fracturing operation on the rock **105** surrounding the interval **505** of the borehole **110** or surrounding rock as described relative to FIG. **5**. However, if the finite element modeling system **445** determines that the rock **105** does not fracture at a breakdown pressure P_b that can reasonably be applied to the rock **105**, the completion system **605** may not include the hydraulic fracturing system **500** and a hydraulic fracturing operation is not performed.

EXAMPLES

[0090] Hereinafter, an example is provided to demonstrate the disclosed method as described in the Detailed Description section.

[0091] Assume rock **105** surrounds an interval **505** of a borehole **110**, the borehole **110** is impermeable, isotropic confining stress σ_c is 22.5 megapascals (MPa), pore pressure p_p is 10 MPa, tensile strength T is 5 MPa, Young's modulus E is 1000 MPa, Poisson's ratio v is 0.2, cohesion strength c is 5 MPa, friction angle ϕ is 30°, dilation angle ψ is 10°, Biot's coefficient β is 1, and initial radius a_0 is 0.1 meters (m).

[0092] The maximum horizontal principal in-situ effective stress σ_{max} **120** and minimum horizontal principal in-situ effective stress σ_{min} **125** may be determined where:

$$P_0=\sigma_{max}=\sigma_{min}=\sigma_c-\beta p_p=22.5-1\cdot 10=12.5\ MPa.$$

The breakdown pressure P_b **205** is determined using Equation (2) as the first model where:

$$P_b=3\sigma_{min}-\sigma_{max}+T+P_p=3\cdot 12.5-12.5+5+10=40\ MPa.$$

The yield pressure P_y **210**_a_ and **210**_b_ is determined using Equation (5) as the second model where:

$$UCS=\frac{2c\cos\phi}{1-\sin\phi}=\frac{2\cdot 5\cos 30^\circ}{1-\sin 30^\circ}=17.3\ MPa,$$

$$N_\phi=\frac{1+\sin\phi}{1-\sin\phi}=\frac{1+\sin 30^\circ}{1-\sin 30^\circ}=3,\text{ and}$$

$$P_y=\frac{UCS+N_\phi(3\sigma_{min}-\sigma_{max})}{N_\phi+1}=\frac{17.32+3(3\cdot 12.5-12.5)}{3+1}=23.1\ MPa.$$

[0093] The elastic model is determined by assuming linear homogenous isotropic elasticity where:

$$G=\frac{E}{2(1+v)}=\frac{1000}{2(1+0.2)}=416.7\ MPa,$$

and plotting P_{elas} relative to

$$\frac{a}{a_0}$$

using Equation (4) as uisprayeu as the elastic model **230** in FIG. **7**.

[0094] The plastic model is determined by plotting P_{plas} relative to

$$\frac{a}{a_0}$$

using Equation (6) as displayed as the plastic model **250** in FIG. **7**.

[0095] FIG. **7** displays an example pressure-displacement curve **200**_a_ in accordance with one or more embodiments. The example pressure-displacement curve **200**_a_ may be used to visually compare the breakdown pressure P_b **205** and yield pressure P_y **210**_a_. Pressure is displayed along the ordinate **700**. Normalized radial displacement a/a_0 of the borehole **110** is displayed along the abscissa **705**.

[0096] Comparing the breakdown pressure P_b **205** of 30 MPa to the yield pressure P_y **210**_a_ of 23.1 MPa, the breakdown pressure P_b **205** is greater than the yield pressure P_y **210**_a_ (i.e., configuration II **240** occurs). Thus, the deformation mechanism and failure mode of the rock **105** includes elastic deformation followed by plastic deformation and ductile fracture, respectively. In some embodiments, as illustrated in FIG. **7**, the rock **105** may elastically deform based on the elastic model **230** of Equation (4), yield at the yield point **245**, and then plastically deform based on the plastic model **250** of Equation (6).

[0097] As such, the finite element modeling system **445** may be configured to determine an updated breakdown pressure P_b. A matrix stimulation operation may be performed below the updated breakdown pressure P_b and/or a hydraulic fracture operation may be performed above the updated breakdown pressure P_b or the borehole **110** along the interval **505** may not be completed.

[0098] Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example embodiments without materially departing from this invention. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims.

What is claimed is:

1. A method comprising:

obtaining, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation;

determining principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data;

determining, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties;

determining, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties;

determining a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure; and

designing, using a completion design system, a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure.

2. The method of claim **1**, wherein the mechanical properties comprise a tensile strength, and

wherein determining the breakdown pressure further comprises using the tensile strength.

3. The method of claim **2**, wherein the mechanical properties further comprise a Biot's coefficient and a Poisson's ratio, and

wherein determining the breakdown pressure further comprises using the Biot's coefficient and the Poisson's ratio.

4. The method of claim **1**, wherein the mechanical properties comprise a friction angle and an unconfined compressive strength, and

wherein determining the yield pressure further comprises using the friction angle and the unconfined compressive strength.

5. The method of claim **1**, further comprising:

using a finite element modeling system:

generating a finite element model of the formation based, at least in part, on the yield pressure, and

determining an updated breakdown pressure of the rock based, at least in part, on the finite element model.

6. The method of claim **5**, wherein the finite element model comprises an elastic model and a plastic model for the rock.

7. The method of claim **1**, further comprising completing, using a completion system, the borehole based, at least in part, on the completion plan.

8. The method of claim **7**, wherein completing the borehole comprises performing, using a hydraulic fracturing system, a hydraulic fracturing operation on the rock surrounding the interval of the borehole.

9. The method of claim **1**, wherein the second model comprises a Mohr-Coulomb failure criterion.

10. The method of claim **1**, wherein the deformation mechanism comprises elastic deformation and the failure mode comprises brittle fracture when the breakdown pressure is less than the yield pressure, and

wherein the deformation mechanism comprises plastic deformation and the failure mode comprises ductile fracture when the breakdown pressure is greater than the yield pressure.

11. A system comprising:

a computer system configured to:

receive, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation,

determine principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data,

determine, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties,

determine, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties, and

determine a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure; and

a completion design system configured to design a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure.

12. The system of claim **11**, further comprising the rock characterization system configured to obtain the rock data.

13. The system of claim **12**, wherein the rock characterization system comprises at least one of a well logging system, a hydraulic fracturing system, and a rock core characterization system.

14. The system of claim **11**, further comprising a finite element modeling system configured to:

generate a finite element model of the formation based, at least in part, on the yield pressure; and

determine an updated breakdown pressure of the rock based, at least in part, on the finite element model.

15. The system of claim **11**, further comprising a completion system configured to complete the borehole based, at least in part, on the completion plan.

16. The system of claim **15**, wherein the completion system comprises a hydraulic fracturing system configured to perform a hydraulic fracturing operation on the rock surrounding the interval of the borehole.

17. The system of claim **11**, wherein the deformation mechanism comprises elastic deformation and the failure mode comprises brittle fracture when the breakdown pressure is less than the yield pressure, and

wherein the deformation mechanism comprises plastic deformation and the failure mode comprises ductile fracture when the breakdown pressure is greater than the yield pressure.

18. A non-transitory computer-readable memory having computer-executable instructions stored thereon that, when executed by a computer processor, perform steps comprising:

receiving, from a rock characterization system, rock data for a rock that surrounds an interval of a borehole within a formation;

determining principal in-situ effective stresses and mechanical properties of the rock using, at least in part, the rock data;

determining, using a first model, a breakdown pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties;

determining, using a second model, a yield pressure for the rock using, at least in part, the principal in-situ effective stresses and the mechanical properties;

determining a deformation mechanism and a failure mode of the rock by comparing the breakdown pressure and the yield pressure; and

designing, using a completion design system, a completion plan for the borehole based, at least in part, on the deformation mechanism, the failure mode, and the breakdown pressure.

19. The non-transitory computer-readable memory of claim **18**, wherein the steps further comprise:

using a finite element modeling system:

generating a finite element model of the formation based, at least in part, on the yield pressure, and

determining an updated breakdown pressure of the rock based, at least in part, on the finite element model.

20. The non-transitory computer-readable memory of claim **18**, wherein the deformation mechanism comprises elastic deformation and the failure mode comprises brittle fracture when the breakdown pressure is less than the yield pressure, and

wherein the deformation mechanism comprises plastic deformation and the failure mode comprises ductile fracture when the breakdown pressure is greater than the yield pressure.

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