



(51) International Patent Classification:

*E21B 21/00* (2006.01)      *G01V 99/00* (2009.01)  
*E21B 49/00* (2006.01)

(21) International Application Number:

PCT/EP2018/058487

(22) International Filing Date:

03 April 2018 (03.04.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

17382170.3      03 April 2017 (03.04.2017)      EP

(71) Applicant: REPSOL, S.A. [ES/ES]; Méndez Álvaro 44,  
28045 Madrid (ES).

(72) Inventors: ALVARELLOS IGLESIAS, Jose; REPSOL,  
S.A., CENTRO TECNOLÓGICO REPSOL (CTR), Car-

retera de Extremadura A-5 Km 18, 28935 Móstoles, Madrid (ES). SEGURA SERRA, José María; REPSOL, S.A., CENTRO TECNOLÓGICO REPSOL (CTR), Carretera de Extremadura A-5 Km 18, 28935 Móstoles, Madrid (ES). IBAÑEZ MARTINEZ, Enric; REPSOL, S.A., CENTRO TECNOLÓGICO REPSOL (CTR), Carretera de Extremadura, A-5. Km 18, 28935 Móstoles, Madrid (ES). MOOKANAHALLIPATNA RAMASESHA, Lakshmi kantha; REPSOL, S.A., CENTRO TECNOLÓGICO REPSOL (CTR), Carretera de Extremadura A-5 Km 18, 28935 Móstoles, Madrid (ES).

(74) Agent: CALVO RAMON, Pablo; ABG PATENTES, S.L., Avda. de Burgos, 16D, Edificio EUROMOR, 28036 Madrid (ES).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,

(54) Title: DRILLING METHOD SUITABLE FOR WELLS FOR THE INJECTION OR PRODUCTION OF A GAS OR OIL RESERVOIR

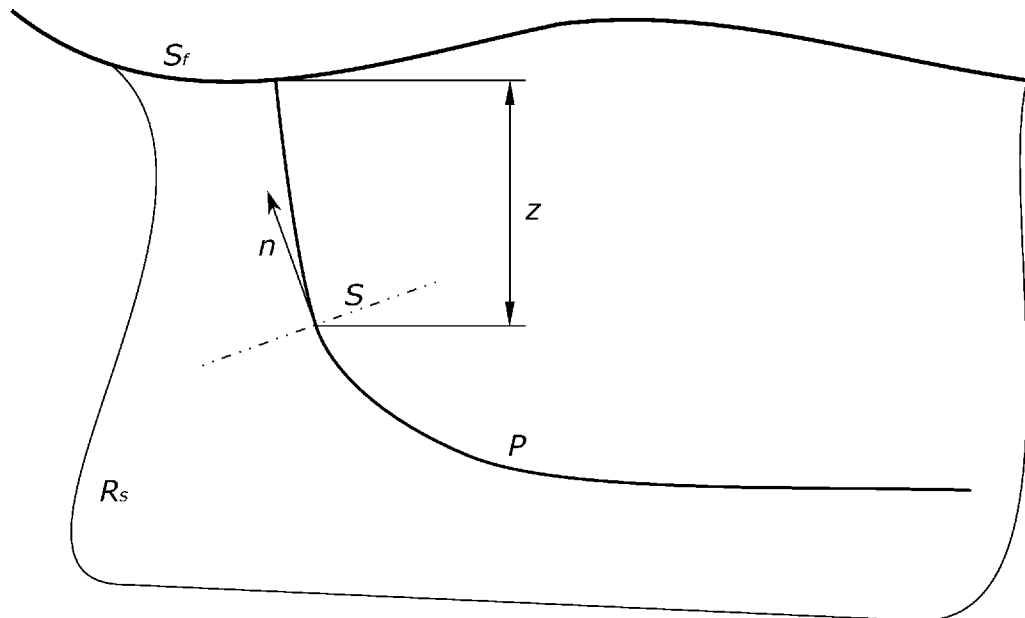


FIG. 1

(57) Abstract: The present invention relates to a drilling method suitable for wells for the injection and production of a gas or oil reservoir. Other uses are in mining and civil engineering work. This method is characterized by the use of the estimation of damage in a plurality of sections along the well to establish the optimal parameters assuring the discharge of caving material without ever reaching the maximum discharge capacity. According to one embodiment, the drilling parameters are determined through an estimation of damage using a set of analytical steps in which not only is the caving angle taken into account, but also the area of damage in each of the sections of the well. This analytical method also allows assessing both the width and the depth of damage in the wall of the well.



DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

**Published:**

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

DRILLING METHOD SUITABLE FOR WELLS FOR THE INJECTION OR  
PRODUCTION OF A GAS OR OIL RESERVOIR

Object of the Invention

5           The present invention relates to a drilling method suitable for wells for the injection and production of a gas or oil reservoir. Other uses can be found in mining and civil engineering work.

10           This method is characterized by the use of the estimation of damage in a plurality of sections along the well to establish the optimal parameters assuring the discharge of caving material without ever reaching the maximum discharge capacity.

15           According to one embodiment, the drilling parameters are determined through an estimation of damage using a set of analytical steps in which not only is the caving angle taken into account, but also the area of damage in each of the sections of the well.

          This analytical method also allows assessing both the width and depth of damage in the wall of the well.

20           Background of the Invention

          Drilling a well for operating gas or oil reservoirs is a very costly project economic wise and the operating conditions for drilling depend on many variables with respect to which there is not always enough data, giving rise to very high values  
25 of uncertainty.

          This uncertainty is much greater in reservoirs in which drilling is performed for the first time where there is usually no data or physical sample that allows increasing knowledge about the geology in the area.

30           Drilling generates an empty tubular space obtained after removing rock that occupied that space. Taking the stress state before drilling and the *in situ* stress as a reference, drilling operations modify the stress state based primarily on two reasons: rock removal eliminates the structural element  
35 compensating for the stress state of the free surface of the generated well; and during drilling, the drilling fluid forms a

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column that exerts pressure on the wall of the well depending primarily on the height to the surface and on the density of said drilling fluid, without taking into account dynamic effects.

5           In fact, one of the parameters to be modified which are used in the drilling operation is the change in density of the drilling fluid in order to change the pressure that is exerted on the wall of the well.

10           There are other causes generating stresses such as the bit in charge of drilling the rock, but they are understood as being required for breaking up and removing rock in the space generated in the well.

15           When the drilling operation uses a drilling fluid, said drilling fluid is usually injected through an inner conduit of the drilling tool. The drilling tool breaks up the rock at the bottom of the borehole generating material having a diverse grain-size distribution that must be removed. The drilling fluid flow injected at the end of the drilling tool entrains this material obtained by drilling rock, flowing upward primarily  
20 through the annular space demarcated between the drilling tool and the already generated wall of the well, until reaching the surface where this material is discharged.

25           The drilling fluid rising up through the annular space exerts pressure against the generated wall of the well. The pressure depends on the weight of the drilling fluid column existing up to the upper surface and also on the speed of the upward flow. The weight of the column is therefore a first estimation of the pressure exerted on the free surface of the wall of the well. A second estimation takes into account the  
30 dynamic stresses of the drilling fluid column according to flow conditions.

35           This pressure may be excessive, exceeding the maximum acceptable stress of the rock generating fractures, for example. Likewise, this pressure may be insufficient and may not compensate for the resistance forces of the removed material to give rise to the well. In this case, the stresses of the rock

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can exceed the acceptable or yielding stress of the rock, causing the material of the wall to break and cave into the well where drilling is being performed.

If this caving occurs during drilling, the drilling fluid  
5 must be capable of discharging the material generated by the drilling tool plus the caving material. The amount of the caving material primarily depends on the volume of rock material that has sustained damage.

Caving occurs in almost all wells. When establishing the  
10 design of the drilling conditions, it is important to quantify the caving in order to assess whether there are drilling parameters that render drilling feasible even if this caving occurs.

After having established well viability, knowing the  
15 optimal drilling parameters under conditions with caving is also of interest.

Analytical modes for assessing damage in rock almost exclusively considering the value of the angle measuring the width of damage in the wall of the well are known in the state  
20 of the art. These analytical techniques use the stress state established by the structure of the rocks forming the reservoir taking into account the *in situ* stresses. These analytical techniques use Kirsch equations, which allow describing the stress state around a well on an infinite plane. There are also  
25 analytical and numerical techniques which allow estimating *in situ* stresses.

The analytical techniques known up until now have considered, hypothetically, that the medium is isotropic and linear, perform all calculations using the original cylindrical  
30 geometry and as a result do not allow correctly calculating the stress around the well and therefore do not allow calculating the depth of damage.

Criteria based solely on the angle covered by the damage in the wall of the well have been developed with techniques of this  
35 type. There is a maximum angle referred to as *angle of collapse*, the value of which is established by each of the companies

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dedicated to drilling. With this criterion, it is possible to establish under which conditions there is considered to be excessive damage: when at a given depth, the angle of damage is found to be greater than the angle of collapse. In this case, it is established that the damage in the wall of the well prevents discharging the caving material during the drilling operation, the well being determined to be unviable.

It has been numerically proven that variation in caving angle with respect to weight of the drilling fluid is approximately linear; nevertheless, the area of damage measured according to a transverse section, and therefore proportional to the caving volume, increases exponentially with respect to the weight of the fluid. In other words, minor variations in the weight of the drilling fluid gives rise to minor variations in the angle of damage (used as parameter in the state of the art), and it generates, however, major variations in the volume of failed rock. The result is an inadequate estimation of the caving volume.

While attempting to reduce the angle of damage, the pressure calculated for the drilling fluid may also exceed the pressure established as the upper limit, i.e., the pressure above which a crack is generated.

This criterion based on the angle of damage in the wall of the well does not take into account the depth of the damage. It has been experimentally found that the described criteria applied according to the state of the art rule out certain wells since they consider that there would be caving which would not allow drilling parameters such that said well may be viable when in practice such wells would indeed be viable. This is the case of caving with a large angle of damage but not very deep, generating a reduced caving volume.

When this occurs, i.e., when it is concluded that a given well is not viable when it actually is, one alternative is to search for another well location. Another alternative is to modify the well path and geometry, reservoirs being able to be ruled out due to the high risk suggested by numerical simulation

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models. Since the first location is usually determined by optimization techniques, the change of well location reduces the optimal character of the initial operating plan, or the change may even require drilling two or more wells in place of the former, significantly increasing costs and reducing production capacity.

The present invention establishes a drilling method optimizing the drilling conditions for each coordinate of the well path. This optimization is based on an estimation of damage for a plurality of sections distributed along the well path.

A specific analytical technique other than that known in the state of the art which allows estimating the region of damage, particularly the width and depth of damage, is of special interest, where this analytical technique allows optimizing the drilling parameters for each coordinate of the well path.

The method of estimating the region of damage according to an example of the invention not only allows calculating with greater precision the optimal drilling parameters taking into account the caving material, but also in those cases where the angle of damage is small but the depth of damage is very large, giving rise to significant caving volumes, the method may consider drilling to be unviable when, by applying techniques based on the state of the art, it would have been accepted, leading to attempts to perform drilling that end in failure and with the loss of resources that this entails.

In wells where the criteria according to the state of the art establish well viability, the parameters obtained according to the invention also allow establishing more favorable drilling conditions, maintaining safety levels that are even higher than those determined in the state of the art.

The determination of the region of damage according to a preferred embodiment allows assessing said region before drilling is performed.

### 35 Description of the Invention

The present invention relates to a drilling method suitable

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for wells using a drilling bit for drilling a well of a well-  
drilling diameter  $D$  at a drilling speed ( $v$ ) and, injecting a  
drilling fluid with a density ( $\gamma$ ) and flow rate ( $Q$ ) during the  
drilling process, for the injection or production of a gas or  
5 oil reservoir. The method comprises the steps of:

- a) *generating a geomechanical model of the domain comprising the  
path of the well to be drilled at least incorporating rock  
data and the mechanical properties of said rock for a pre-  
specified in situ stress field;*
- 10 b) *generating a fluid flow model of the same domain at least  
incorporating drilling fluid data, wherein said fluid flow  
model models the rock as a porous medium and comprises the  
pore pressure in said porous medium.*

The domain is a pre-specified region comprising the path of  
15 the well to be drilled. Taking gas or oil reservoirs as an  
example, these reservoirs are formed primarily by porous rocks  
that store gas or oil trapped in the pores. The domain can  
contain the reservoir and be more extensive to the point of  
including the portion of rock reaching the surface of the earth.  
20 It can also be smaller than the reservoir, containing only a  
part of said reservoir, although it must indeed contain the path  
to be drilled. In applications of another type, the fluid can be  
water, for example. The mechanical behavior of the rock depends  
both on the mechanical properties of the rock and on the  
25 influence of the fluid trapped in the pores of the rock due to  
the pressure at which said fluid is found. Particularly, at  
least the mechanical properties of the rock, the properties of  
the fluid trapped in the rock and also the drilling fluid which  
is in contact with the generated surface of the well are  
30 relevant.

In one embodiment, steps a) and b) are carried out by means  
of a computational system.

In order to establish the stress state of the well, it is  
necessary to generate a geomechanical model of the reservoir  
35 incorporating these properties as well as the *in situ* stress  
field and the boundary conditions or the boundary conditions and

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the initial conditions if the model is based on an initial value problem also taking dynamic variables into account.

The geomechanical and fluid flow models allow reproducing the behaviour of the rock in the drilling conditions for  
5 determining the stresses causing damage under the simplifying hypotheses of the models used.

*c) establishing a drilling diameter  $D$  and a well path through the geomechanical model and the fluid flow model of the domain;*

10 *d) establishing a discretization  $t_i = 1..N$  of the coordinate ( $t$ ) along the well path.*

The boreholes do not necessarily have to be vertical and straight. For example, the search for hydrocarbon sources may require tracing paths that navigate through very hard rocks,  
15 regions with rather unstable sand, or horizontal paths in the final segments making easy subsequent harnessing of those resources.

After having established the geomechanical and fluid flow models, the path and a discretization along the path are  
20 determined in such models. A specific way of defining the path is by means of a piecewise or non-piecewise parametric curve. The points  $t_i$  are specific points of the curve where damage in the rock causing caving will be assessed and thereby estimating at those points the volume of caved rock which increases the  
25 drilling fluid discharge requirements. The higher the density of points is, the greater the number of evaluations of damage there will be, but precision in the calculation of the caving volume according to a coordinate or parameter ( $t$ ) which follows along the path will also be greater.

30 *e) determining, for each  $t_i$ , a transverse section  $S_i$  of diameter  $D$ , and in said section  $S_i$ , for one or more values of density of the drilling fluid  $\gamma_j^l, j = 1..M$ :*

*i. determining the pore pressure  $p_p$ , vertical height  $z_i$ , maximum stress  $\sigma_{max}$ , minimum stress  $\sigma_{min}$  and the  
35 mechanical properties of the rock in the section based*

on the geomechanical model;

- ii. determining the stress state of the rock in said section  $S_i$  at least according to the data from the preceding step;
- 5 iii. determining in section  $S_i$  the region  $R_j^i(\gamma_j^l, S_i)$  of damage under a pre-established rock failure criterion and the value of the area  $A_j^i(\gamma_j^l, S_i) = \|R_j^i(\gamma_j^l, S_i)\|$  of said region  $R_j^i(\gamma_j^l, S_i)$ .

A section is determined for each of the points  $t_i = 1..N$  of  
 10 the discretization of the well path. The damage for different conditions of the pressure fluid is analyzed in this section, which allows generating a discrete function which in turn allows determining under which conditions drilling can be performed.

For this reason, a discrete set  $M$  of densities of the  
 15 drilling fluid  $\gamma_j^l, j = 1..M$  is established.

In each section, the forces acting on the rock (pore pressure  $p_p$ , maximum stress  $\sigma_{max}$ , and minimum stress  $\sigma_{min}$ ) and also the strength properties thereof are evaluated for determining the stress state of the rock in said section  $S_i$ .

20 Damage is calculated with the resistance capacity of the rock and the forces acting thereon once a failure criterion of the rock has been established.

A damaged area, identified as region  $R_j^i(\gamma_j^l, S_i)$ , within section  $S_i$ , is established with the failure criterion.

25 The more precise the method of determining the region of damage is, the better the estimation of the rock caving volume will be.

According to a preferred example, the damage is determined by hypothetically assuming that the damaged area is in an  
 30 elliptical sector and is evaluated by establishing an analytical method that will be described below for determining the dimensions of the ellipse that penetrates the rock.

f) for each coordinate  $(t)$  of the discretization  $t_i = 1..N$  establishing:

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- iv. a correspondence  $V^i(\gamma_j^l)$  between the discrete values of density of the drilling fluid  $\gamma_j^l, j=1..M$  and the value of the area  $A_j^i(\gamma_j^l, S_i)$ , the latter being interpreted as the detachment volume ( $V$ ) of the wall of the well per unit of drilled length;
- v. a combination of drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) thereof, such that it establishes a volume of material  $V_e(v, \gamma, Q)$  to be discharged, material being cut by the bit plus the caving material  $V^i(\gamma_j^l)$ , less than that determined by the drilling system, so as to allow removing the volume of material from the well without the drilling bit collapsing;
- g) drilling the well according to the values of drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) thereof for each coordinate of the well path.

The value of the area  $A = \|R\|$  of said region  $R$  of damage is interpreted as the additional volume per unit of length that must be displaced or cleared during drilling. Obtaining different regions of damage for each of the discretization points allows determining a caving volume according to each point of the path. This variable function gives rise to a different clearing volume which can affect the drilling speed or the pressure within the system (pressure of the fluid in the annular). This variable (caving volume) can then be used for adjusting the drilling speed, weight of the flows and/or pressure of the drilling fluid, being adjusted to the optimal conditions at all times.

Given that a calculation of the value of the area  $A = \|R\|$  of the region  $R$  of damage is established for each discrete value of the density of the drilling fluid  $\gamma_j^l, j=1..M$ , a function  $V(\gamma)$ , the caving volume, is established where the dependence has been obtained in a set of discrete samples.

The combination of drilling speed ( $v$ ), density ( $\gamma$ ) of the

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injected drilling fluid and flow rate ( $Q$ ) thereof can be established at each discretization point of the path such that it establishes a volume of material  $V_e(v, \gamma, Q)$  to be discharged, material being cut by the bit plus the caving material  $V^i(\gamma_j^l)$ ,  
5 less than that determined by the drilling system, so as to allow removing the volume of material without the drilling bit collapsing. A person skilled in drilling knows how much material can be removed by the drilling system depending on the density ( $\gamma$ ) of the injected drilling fluid and the flow rate ( $Q$ ).  
10 According to the invention, the skilled person can determine the drilling speed ( $v$ ), the density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) for each coordinate of the well path as for each density ( $\gamma$ ) he knows the volume of the caving material  $V^i(\gamma_j^l)$ .

15 The values of the area  $A = \|R\|$  of damage, and therefore the caving volume, can be determined at points not within the discretization, for example, by interpolating the (scalar) values obtained at adjacent points.

The material being cut by the bit is determined by the  
20 drilling speed ( $v$ ) and the section of well being drilled.

The drilling parameters used along the pre-established path are obtained with these values.

#### Description of the Drawings

The foregoing and other features and advantages of the  
25 invention will be more clearly understood based on the following detailed description of a preferred embodiment, provided only by way of illustrative and non-limiting example in reference to the attached drawings.

Figure 1 shows a diagram for making a well in an oil  
30 reservoir, defined by a well path, where a section  $S$  on which the region of damage is determined is established at a given point of the path.

Figure 2 shows a diagram for making a well in a sectional  
view, as well as a pair of ellipses with different eccentricity  
35 used in the calculation steps according to an example of the

invention.

Figure 3 shows a graph of stresses on the periphery of a family of ellipses. The family of ellipses is represented by means of a plurality of curves identified with an arrow in which  
5 the direction in which the eccentricity increases is shown. The abscissas show the angle in the section taking the point of minimum stress as a reference.

Figure 4 shows an image of a vertical segment of the well in which the width of the damage has been measured according to  
10 the vertical height. Regions with damage are darker.

Figure 5 shows two graphs related to one another. The graph on the left shows a drawing with the factor of safety  $F$  according to the eccentricity  $e$  with a value of one to consider the factor of equilibrium between the external forces and  
15 resistance forces. After having determined the eccentricity, the graph on the right shows the ellipse with said eccentricity determining the transverse area of the damage.

Figure 6 partially reproduces Figure 1 as an embodiment where the determination of damage is carried out in a discrete  
20 set of the well path for subsequently evaluating the caving volume, and therefore for performing drilling according to the parameters estimated according to an embodiment.

#### Detailed Description of the Invention

According to the first inventive aspect, the present  
25 invention relates to a drilling method suitable for wells for the injection or production of a gas or oil reservoir. A preferred example proposes a method which allows estimating the region of damage due to caving in the wall of a well during the drilling operation for the injection or production of a gas or  
30 oil reservoir.

Figure 1 schematically shows the section of a reservoir with oil reserves, where the upper line represents the surface of the reservoir and the volume of the reservoir identified by the lower line ( $R_s$ ), a well ( $P$ ) being demarcated therein.

35 The well ( $P$ ) is a well having a circular section  $S$  extending along a path depicted by a curve. The curve is shown

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in Figure 1 beginning at the surface, descending in an almost vertical path, and after increasing its inclination ending in an almost horizontal segment.

The drilling parameters which allow drilling in optimal  
5 conditions are to be determined along this path.

In a first step, a geomechanical model of the reservoir incorporating at least rock data and the mechanical properties of said rock under the conditions determining a pre-specified *in situ* stress field is generated in a computational system.

10 The stresses in the rock are not determined only by the *in situ* stresses and the properties at each point of the domain of the geomechanical model, but they also depend on the dynamic pressure and fluid conditions of the fluids stored in the rock. These variables are established by generating a fluid flow model  
15 of the same reservoir in the computational system. A preferred way of reservoir modeling includes a geomechanical model and a fluid flow model coupled to one another where changes in the pressure field in the fluid flow model are taken into account in the geomechanical model and deformations and changes in porosity  
20 and permeability properties are taken into account in the fluid flow model.

In addition to the path, other parameters, such as the drilling diameter, are also determined.

Once the path has been determined by means of a curve  
25 contained in the domain of the geomechanical and fluid flow models, a discretization  $t_i = 1..N$  of the coordinate ( $t$ ) along the well path is established. The coordinate  $t$  is a coordinate parametrizing the course of the well path.

The values of pore pressure  $p_p$ , vertical height  $z_i$ , maximum  
30 stress  $\sigma_{max}$ , minimum stress  $\sigma_{min}$  and the mechanical properties of the rock in the section based on the geomechanical model are determined at each of the discretization points.

These values allow calculating the stress state at each discretization point of the path.

35 According to the stress state, for each discretization

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point the perpendicular section  $S_i$  is determined, and in said section, the region  $R(\gamma_j^l, S_i)$  of damage under a pre-established rock failure criterion and the value of the area  $A = ||R||$  of said region  $R$  are determined.

5 According to a preferred example, the region of damage is calculated by proposing a configuration of the damage in the section according to an elliptical shape which is determined as described below.

Figure 1 shows a path where the region of damage in a section  $S$  located at a height  $z$  is to be calculated. At this height  $z$ , the tangent  $n$  to the path coincides with the normal to the transverse plane of section where the region of damage is to be determined. The subscript "i" has been eliminated given that a specific point  $t_i$  is considered. The path is contained in a domain  $R_s$  demarcated in the upper portion by the surface  $S_f$ .

This same drawing depicts by means of a dashed line the plane transverse to the drilling path of the well at a pre-established point.

Figure 2 schematically shows a circumference in a thick line representing the theoretical wall of the well in the plane of section  $S$ .

Given the direction normal to the plane of section  $S$ , by means of rotation about said normal a direction where stress is minimum  $\sigma_{min}$  and a direction which is perpendicular to the preceding direction, where stress is maximum  $\sigma_{max}$ , are established. These directions are those used as the axes of reference for establishing the site where damage occurs and its extent.

After having established the axes, the stress state in the rock along the curve defined by the circumference corresponding to the wall of the well is determined based on the geomechanical model. The value of the equivalent stress is calculated based on the stress state determining, from this calculation, the arc of a curve where said equivalent stress is greater than the acceptable stress of the rock.

This arc is centered in  $\pi/2$  due to the way of constructing the axes of reference and the width thereof is the caving angle  $\theta_{br}$ .

Figure 2 shows both axes which are axes that will correspond to the major and minor sides of a family of ellipses. This family of ellipses is parameterized by means of the eccentricity  $e$  defined as  $a/b$ . For a value of eccentricity equal to 1, the ellipse is the circumference having a radius  $R$  corresponding to the circumference representing the wall of the well according to section  $S$ . For increasing values of eccentricity  $e$ , ellipses having one end of the major side penetrating the rock while the minor side being smaller than the radius of the well  $R$ , are obtained. Of the ellipses thus obtained, the part of the ellipse which penetrates the rock and which will be the curve defining the region of damage will be of special interest.

The points where the caving angle starts and ends are the points where the intersection between the circumference and any of the ellipses of the parameterized family in  $e$  is established.

The values of  $a$  and  $b$  in Figure 2 identify the length and width of a given ellipse. Two ellipses of eccentricity  $e_1$  and  $e_0$  are also shown.

The factor of safety is used to determine the ellipse defining the region of damage

$$F = \frac{\sum \sigma_{ext}}{\sum \sigma_{res}}$$

where  $\sum \sigma_{ext}$  is the sum of external forces on the rock at a given point of the rock, depending at least on the *in situ* stresses, on the density ( $\gamma$ ) of the drilling fluid, on the elastic properties of the rock and on the pore pressure  $p_p$ ; and

where  $\sum \sigma_{res}$  is the sum of resistance forces of the rock at the same point, depending on the stress tensor, on the strength properties of the rock and on the angle of internal friction of the rock.

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This factor of safety depends on the angle and on the factor of eccentricity where the value of one identifies the equilibrium between the forces and the resistance capacity. Damage is deemed to exist when this equilibrium is broken. 5 Nevertheless, it is possible for a person skilled in the art to select values  $f_0$  other than but close to one as the factor of safety, for example. Valid  $f_0$  values are those comprised in the [0.7, 1.3] range, and more preferably in the [0.8, 1.2] range, and more preferably in the [0.9, 1.1] range and more preferably 10 in the [0.95, 1.05] range.

Figure 3 shows a graph of stress according to the angle  $\theta$  where for values close to  $\pi/2$ , identified in the drawing as close to 90 given that it is expressed in degrees instead of radians, the stress acquires asymptotically high values as 15 eccentricity increases.

This fact renders the approach according to the state of the art for the estimation of damage useless since in no case would it consider that a safe situation exists.

With this hypothesis, the area of the end of the ellipse 20 reaches unacceptable values in almost any case which would invalidate this method of determining the region of damage. Nevertheless, it has been found that if this bias is overcome by eliminating values above the pre-specified value  $\theta_0 < \pi/2$ , then the method predicts with great precision the region of damage.

25 After having established  $\theta_0 < \pi/2$ , the value of eccentricity  $e_0$  closest to one is determined, verifying  $F(\theta_0, e_0) = f_0$ , where  $f_0$  is the pre-established reference value close to one.

Figure 4 shows an image of the perforated wall in a well, showing the areas where damage has occurred. The letters N, E, S 30 and W identify North, East, South and West, respectively, and correspond to a perimetral development of 360 degrees ( $2\pi$  radians).

The image is taken a *posteriori*, once the well has been drilled or obtained by sensing during drilling. The dark spots 35 are areas of damage in the wall based on which it is possible to

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determine the width of damage at a given vertical height  $z$  but they do not allow establishing the depth in the wall or providing the determination thereof before drilling is performed.

5           Figure 5 shows a graph of the function  $F(\theta_0, e) = f_0 = 1$  with eccentricity  $e$  as a free parameter. It is where the function takes this value  $f_0 = 1$ , i.e., the value which determines the eccentricity  $e$  which in turn defines a single ellipse of the family of ellipses defined above.

10           In this embodiment, the ellipse has an eccentricity of 0.4. The right hand side of the drawing shows a quarter of a circumference, the circumference representing the section of the wall of the well, and also a quarter of the ellipse having an eccentricity of 0.4. The inner area of the ellipse having an  
15 eccentricity of 0.4 is established as the region of damage.

          Given this region of damage, it is possible to repeat the method for a plurality of sections  $S$  distributed along the well path, particularly the discretization  $t_i = 1..N$  along the well path. By means of interpolating the sections of damage along a  
20 segment of the well path, it is possible to determine the caving volume in that segment before drilling is performed.

          With the caving volume, it is possible to establish drilling fluid injection parameters which allow discharging the caved volume. Otherwise, the method allows recalculating the  
25 caving volume by changing the pressure conditions established by the drilling fluid. For example, if the density  $\gamma$  of the drilling fluid increases, the pressure on the walls of the well increases and compensates for the stresses exerted by the eliminated rock on the well and giving rise to the free surface,  
30 given that they now no longer perform a structural function. The region of damage is thereby reduced given that the pressure forces against the wall exert this compensating force.

          This force has a limit since an excessive increase in the density of the drilling fluid can cause a pressure that is too  
35 high to be withstood by the wall of the well, generating cracks.

Therefore, this embodiment shows how the region of damage depends on the parameters used in the calculation of the stress state at the point where the plane of section  $S$  has been plotted out, and particularly on the pressure of the drilling fluid.

5 It is possible to simulate different conditions of damage for a plurality of densities of the drilling fluid and establish those that give rise to a caving volume less than the limit acceptable by the means installed in the well. In other words, a correspondence  $V^i(\gamma_j^l)$  between the discrete values of density of  
10 the drilling fluid  $\gamma_j^l, j = 1..M$  and the value of the area  $A_j^i(\gamma_j^l, S_i)$  of damage is determined, the latter being interpreted as the detachment volume ( $V$ ) of the wall of the well per unit of drilled length.

With this correspondence and for each of the sections along  
15 the discretization  $t_i = 1..N$ , a combination of drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) thereof is determined, such that it establishes a material to be discharged  $V_e(v, \gamma, Q)$ , material being cut by the bit plus the  
20 caving material  $V^i(\gamma_j^l)$ , less than that determined by the drilling system.

The volume determined by the drilling system is determined by the skilled person needing the density of the drilling fluid ( $\gamma$ ) and flow rate ( $Q$ ) for determining said maximum volume of the  
25 drilling system so as to allow removing the volume of material detaching from the well without the drilling bit collapsing.

After having determined the drilling parameters, drilling is carried out according to the values of drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) thereof for each coordinate of the well path.

30 The drilling operation discharges the sum of two volumes of material, the material being cut by the bit plus the material being caved near the bit because the damaged area corresponds to material showing a stress greater than the allowable stress of the rock in that location and then it further collapses. The sum  
35 of the two volumes is discharged by the injected drilling fluid.

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An skilled person on drilling systems, according to his practice, determines the maximum volume of material to be discharged by the drilling system.

This skilled person is able to determine the volume of  
5 material to be discharged depending at least on the density and the flow rate of the drilling fluid being injected.

The invention provides the correspondence  $V^i(\gamma_j^l)$ , the volume being detached when drilling, to the skilled person and therefore solves the problem determining a volume of material to  
10 be discharged being less than that determined by the drilling system. The rest of the feature is just a clarification indicating that the result of using the combination of parameters (drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) fulfilling the specified  
15 condition allows removing the volume of material from the well without a drilling bit collapsing.

As described, it is possible to use an alternative method as a preferred way of determining the damage in a section of the well before drilling is performed: calculating the stress state  
20 by means of a geomechanical and fluid flow model numerical resolution method, for example, by means of finite elements. The region exceeding the acceptable stress is determined with this calculation for each value of the density of the drilling fluid, establishing said region as the region of damage.

25 In any of the particular ways of calculating the damage, according to another embodiment, the dynamic effects of the drilling fluid flow are taken into account. The dynamic effects can be interpreted in terms of pressure variations in a drilling fluid column with respect to static pressure.

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CLAIMS

1. A drilling method suitable for wells using a drilling bit for drilling a well of a well-drilling diameter  $D$  at a drilling speed ( $v$ ) and, injecting a drilling fluid with a density ( $\gamma$ ) and flow rate ( $Q$ ) during the drilling process, for the injection or production of a gas or oil reservoir, comprising the steps of:
- a) generating a geomechanical model of the domain comprising the path of the well to be drilled at least incorporating rock data and the mechanical properties of said rock for a pre-specified *in situ* stress field;
  - b) generating a fluid flow model of the same domain at least incorporating drilling fluid data, wherein said fluid flow model models the rock as a porous medium and comprises the pore pressure in said porous medium;
  - c) establishing a drilling diameter  $D$  and a well path through the geomechanical model and the fluid flow model of the domain;
  - d) establishing a discretization  $t_i = 1..N$  of the coordinate ( $t$ ) along the well path;
  - e) determining, for each  $t_i$ , a transverse section  $S_i$  of diameter  $D$ , and in said section  $S_i$ , for one or more values of density of the drilling fluid  $\gamma_j^l, j = 1..M$ :
    - i. determining the pore pressure  $p_p$ , vertical height  $z_i$ , maximum stress  $\sigma_{max}$ , minimum stress  $\sigma_{min}$  and the mechanical properties of the rock in the section based on the geomechanical model;
    - ii. determining the stress state of the rock in said section  $S_i$  at least according to the data from the preceding step;
    - iii. determining in section  $S_i$  the region  $R_j^i(\gamma_j^l, S_i)$  of damage under a pre-established rock failure criterion and the value of the area  $A_j^i(\gamma_j^l, S_i) = \|R_j^i(\gamma_j^l, S_i)\|$  of said region

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$$R_j^i(\gamma_j^l, S_i);$$

f) establishing, for each coordinate ( $t$ ) of the discretization  $t_i = 1..N$ :

- i. a correspondence  $V^i(\gamma_j^l)$  between the discrete values of density of the drilling fluid  $\gamma_j^l, j = 1..M$  and the value of the area  $A_j^i(\gamma_j^l, S_i)$ , the latter being interpreted as the detachment volume ( $V$ ) of the wall of the well per unit of drilled length;
  - ii. a combination of drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) thereof, such that it establishes a volume of material  $V_e(v, \gamma, Q)$  to be discharged, material being cut by the bit plus the caving material  $V^i(\gamma_j^l)$ , less than that determined by the drilling system, so as to allow removing the volume of material from the well without the drilling bit collapsing;
- g) drilling the well according to the values of drilling speed ( $v$ ), density ( $\gamma$ ) of the injected drilling fluid and flow rate ( $Q$ ) thereof for each coordinate of the well path.

2. The method according to claim 1, wherein in step e) ii) the stress state of the rock is determined by means of a numerical discretization method of both the geomechanical model and the fluid flow model in the domain established by section  $S_i$ .

3. The method according to claim 1, wherein in step e) ii) the stress state of the rock is determined by means of:

- Kirsch equations,
  - Mohr-Coulomb equations, or
  - the Lade and Drucker-Prager equations
- on the geomechanical model taking into account the pressure established by the slurry according to the fluid flow model in the domain established by section  $S_i$ .

4. The method according to any of the preceding claims, wherein in step e) iii) the rock failure criterion for determining the region  $R_j^i(\gamma_j^l, S_i)$  of damage is the breaking stress.

5. The method according to any of the preceding claims, wherein in step e) iii) the rock failure criterion for determining the region  $R_j^i(\gamma_j^l, S_i)$  of damage comprises the steps of:

- determining the stress state  $\sigma(\theta)$  of the rock on the periphery of section  $S_i$  of the well at least according to the data from the geomechanical model, wherein:
  - i.  $\sigma$  is the scalar value of the equivalent stress,
  - ii.  $\theta$  is the angle with respect to a system of axes located in section  $S_i$  of the well, centered in the center of said section  $S_i$  and with an orientation on the plane containing section  $S_i$ , such that  $\sigma(\theta = 0) = \sigma_{min}$  and  $\sigma(\theta = \pi/2) = \sigma_{max}$ ;
- determining the caving angle  $\theta_{br}$  as the angle centered in  $\theta = \pi/2$  and covering the arc of the periphery of section  $S$  where the stress  $\sigma(\theta)$  is greater than the acceptable stress of the rock;
- defining the family of ellipses of eccentricity  $e = a/b$ ,  $a$  being the semi-minor side and  $b$  the semi-major side of the ellipse, contained on the plane of section  $S_i$ , such that:
  - iii. the ellipse corresponding to the value of eccentricity  $e = 1$  is the circumference established by the circular section  $S_i$  of the well; and
  - iv. the intersection between the ellipse and the circular section  $S_i$  of the well is established at least at points  $\pi/2 + \theta_{br}/2$  and  $\pi/2 - \theta_{br}/2$  as well as at their symmetrical points  $-\pi/2 + \theta_{br}/2$  and  $-\pi/2 - \theta_{br}/2$ , respectively;
- defining a factor of safety

$$F = \frac{\sum \sigma_{ext}}{\sum \sigma_{res}}$$

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where  $\sum \sigma_{ext}$  is the sum of external forces on the rock at a given point of the rock, depending at least on *in situ* stresses, on the density ( $\gamma$ ) of the drilling fluid should there be any, on the elastic properties of the rock and on the pore pressure  $p_p$ ; and

5 where  $\sum \sigma_{res}$  is the sum of resistance forces of the rock at the same point, depending on the stress tensor, on the strength properties of the rock and on the angle of internal friction of the rock;

- determining the function  $F(\theta, e)$  as the factor of safety  $F$  10 evaluated at a point of the ellipse defined by the eccentricity  $e$  for a value of the angle  $\theta$ ;
- establishing a cut-off threshold value  $\theta_0 < \pi/2$ ;
- determining the value of eccentricity  $e_0$  closest to one verifying  $F(\theta_0, e_0) = f_0$ , where  $f_0$  is a pre-established reference 15 value close to one;
- establishing the intersection region between the ellipse of eccentricity  $e_0$  and the circumference of section  $S$  of the well as the region of damage  $R_j^i(\gamma_j^l, S_i)$  according to section  $S_i$  of the well and at vertical height  $z_i$ .

20

6. The method according to claim 5, wherein the estimation of the depth of the damage  $b_d$  in the wall is calculated as the difference between the semi-major side  $b$  of the ellipse of eccentricity  $e_0$  and the radius of the circumference of section  $S$  25 of the well.

7. The method according to any of claims 5 to 6, wherein the estimation of the width angle of damage in the wall is calculated as the angle covering the intersecting points between 30 the ellipse of eccentricity  $e_0$  and the circumference of the section of the well.

8. The method according to any of claims 5 to 7, wherein the estimation of stress at a point of the rock determined by an

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ellipse of eccentricity  $e$  takes the following value:

$$\sigma(\theta, e) = \frac{R}{\sqrt{\cos^2 \theta + e^2 \sin^2 \theta}} \sigma_{max}$$

$R$  being the radius of section  $S$  of the well.

9. The method according to any of the preceding claims,  
5 wherein the correspondence  $V^i(\gamma_j^l)$  is a continuous function  
determined from the samples  $A_j^i(\gamma_j^l, S_i)$  for all  $j = 1..M$  in section  $S_i$ .

10. The method according to any of the preceding claims,  
wherein in the calculation of the stress state of the rock in  
10 step e) ii) and in section  $S_i$ , the dynamic effects of the  
drilling fluid flow are included in the fluid flow model.

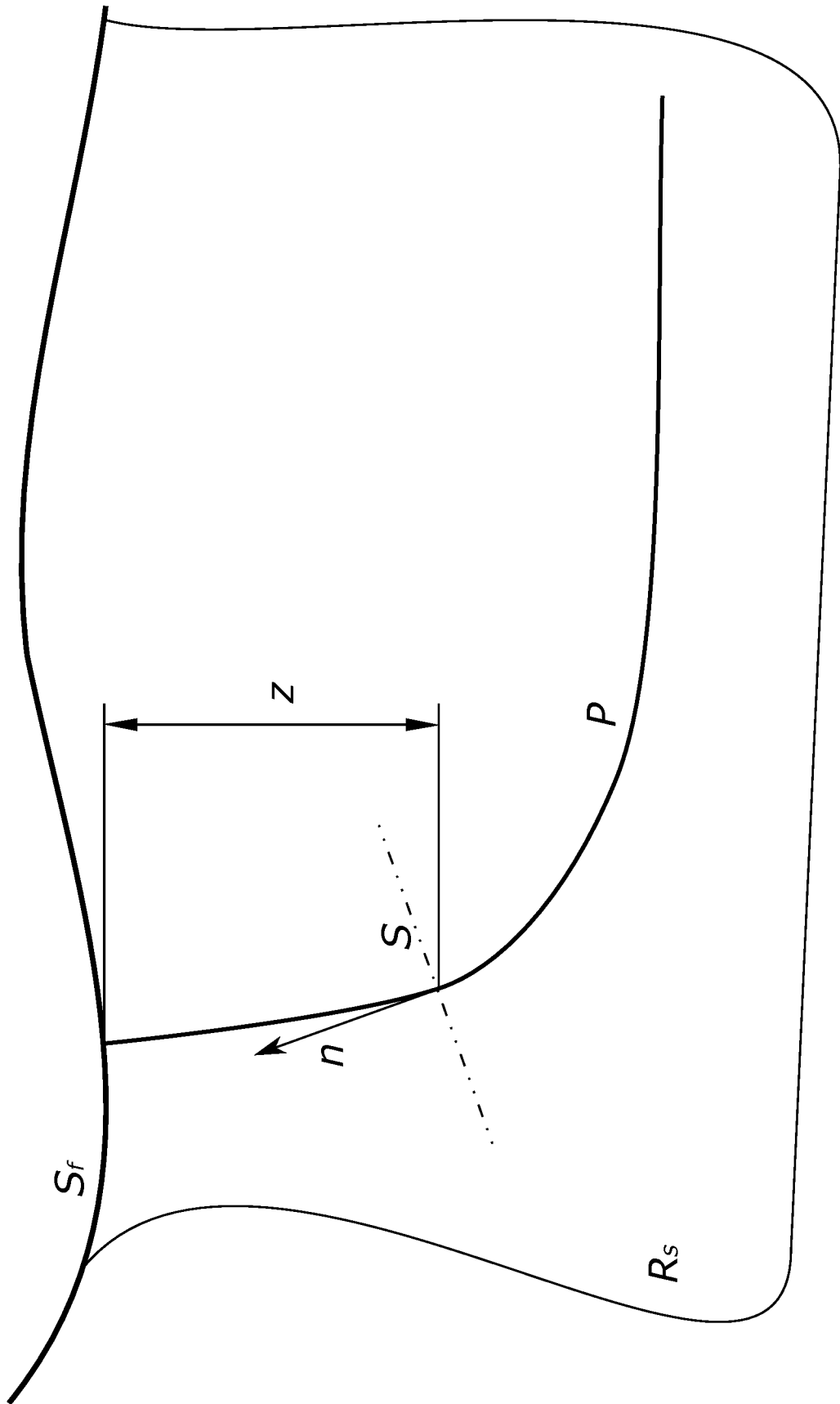


FIG. 1

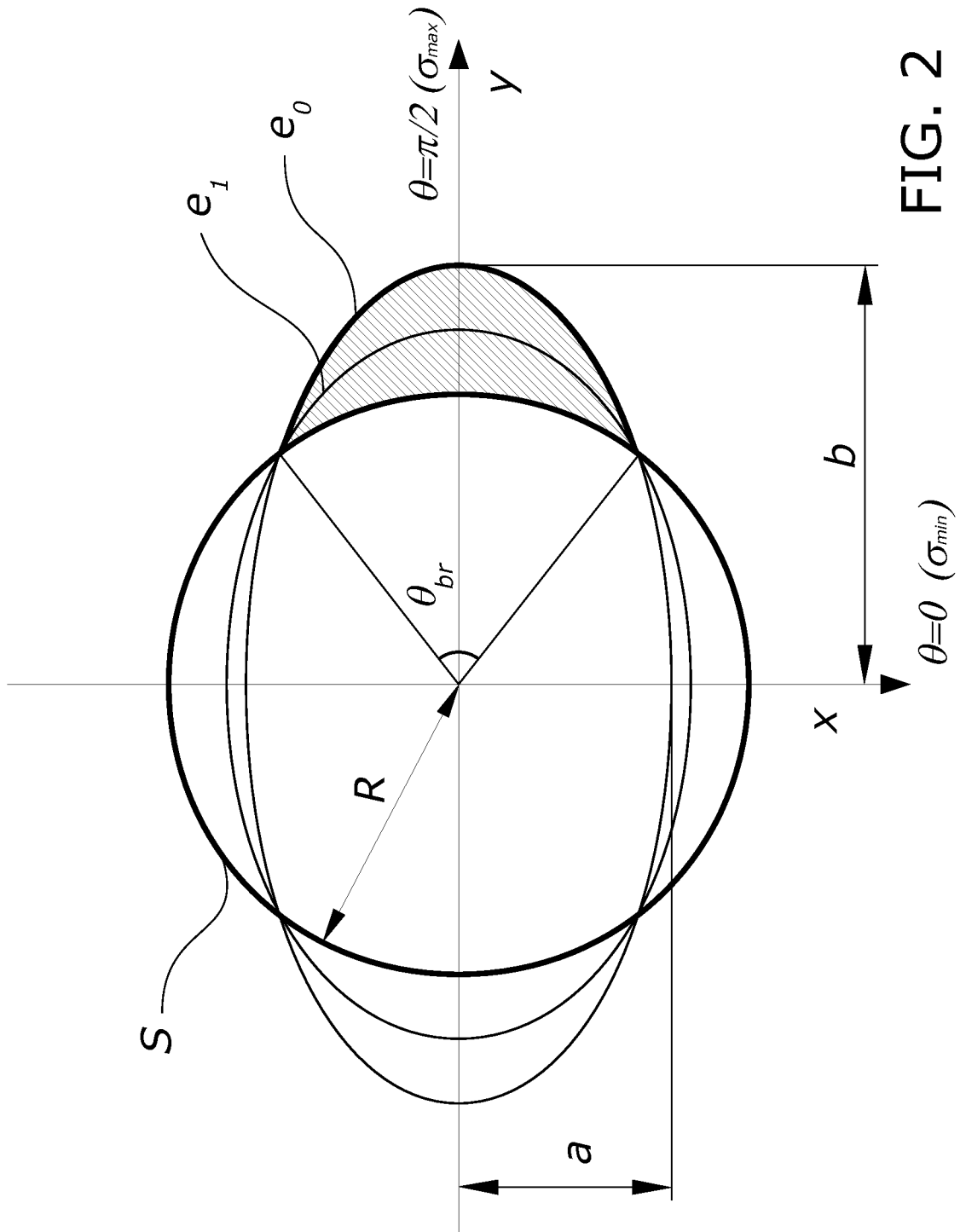


FIG. 2

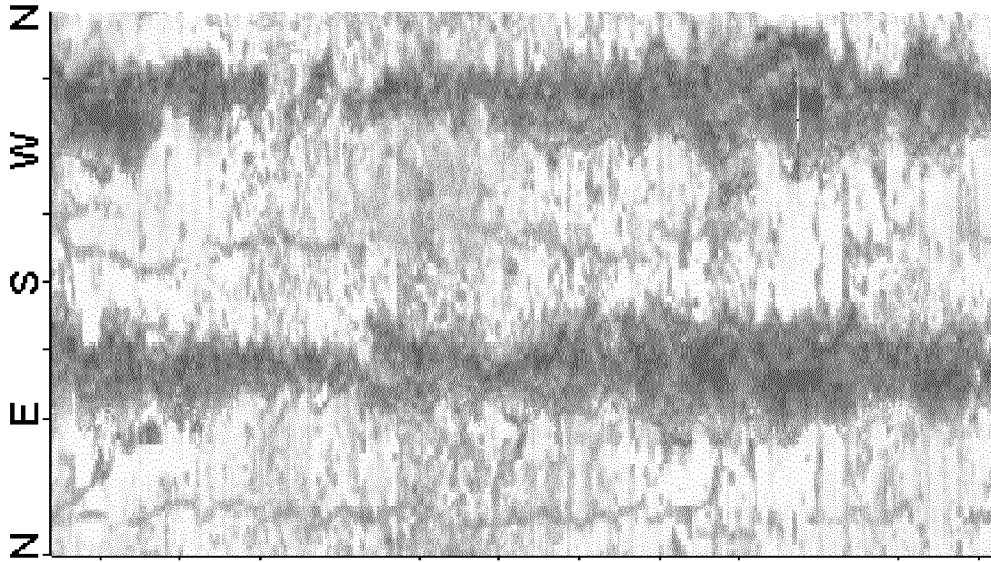


FIG. 4

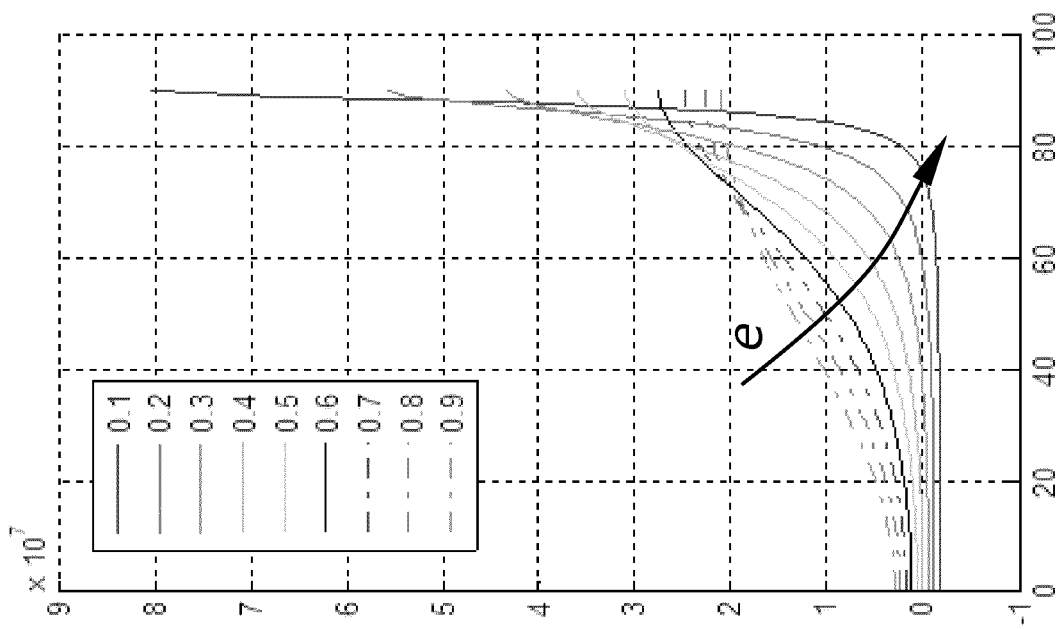


FIG. 3

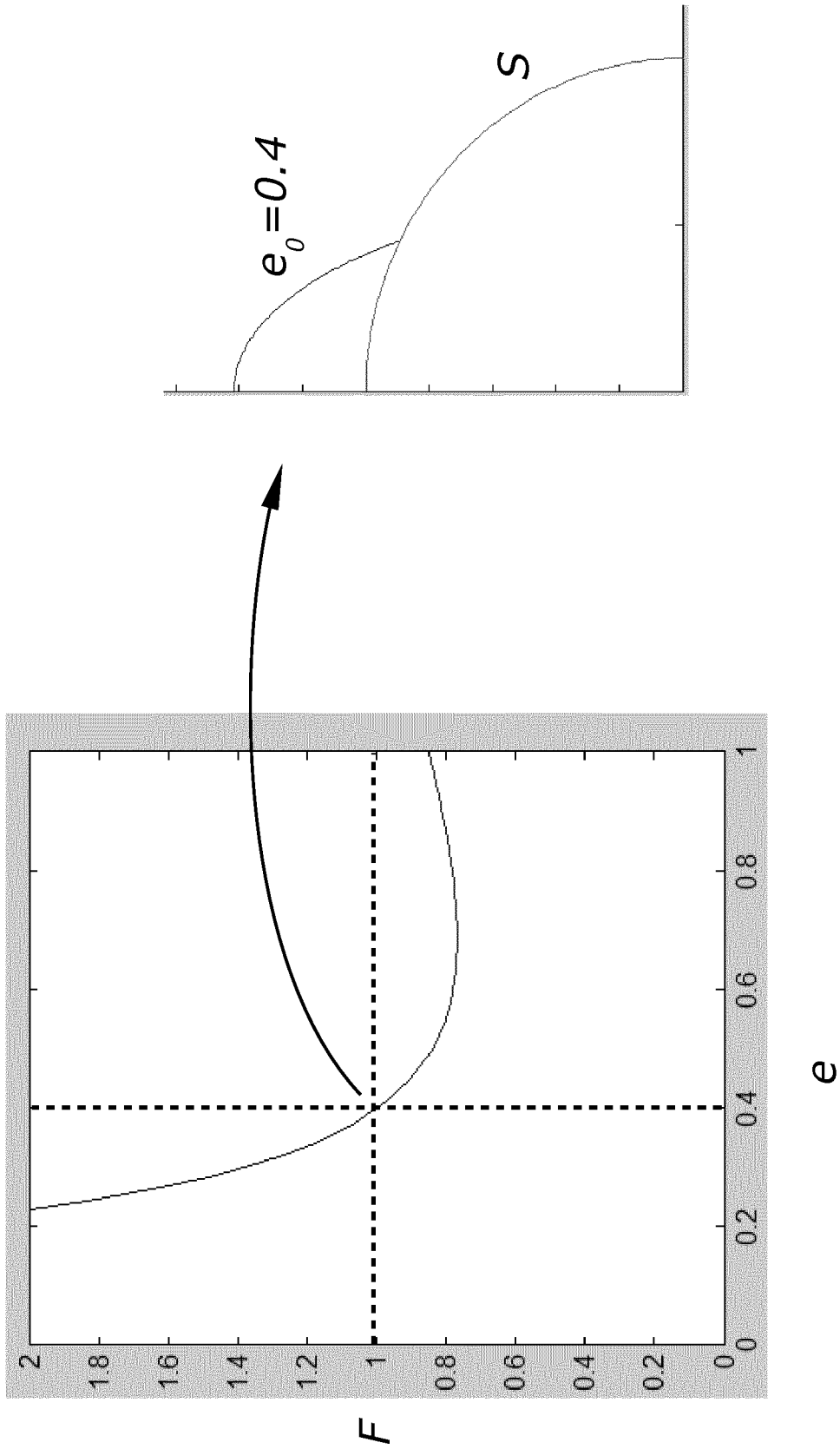


FIG. 5

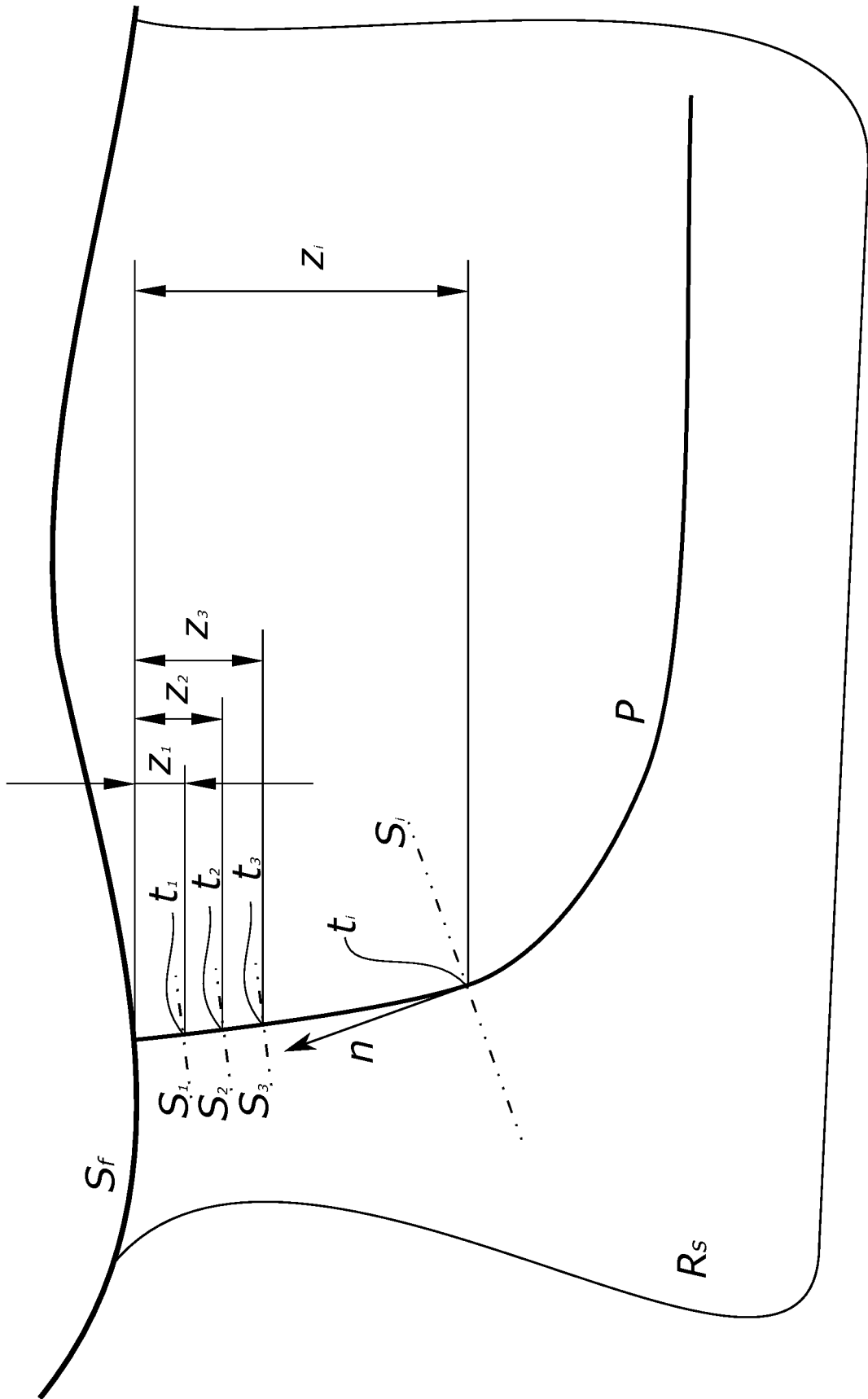


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2018/058487

A. CLASSIFICATION OF SUBJECT MATTER  
INV. E21B21/00 E21B49/00 G01V99/00  
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 G01V

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2013/112114 A1 (LANDMARK GRAPHICS CORP [US]; SHEN XINPU [US]) 1 August 2013 (2013-08-01) the whole document ----- -/--	1

Further documents are listed in the continuation of Box C.

See patent family annex.

\* Special categories of cited documents :

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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Date of the actual completion of the international search  7 June 2018	Date of mailing of the international search report  15/06/2018
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer  van Berlo, André
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## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2018/058487

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>J Segura ET AL: "Fault-stability-assessment-for-well-planning-a-case-study-related-to-salt-structures", 1 January 2016 (2016-01-01), XP055405285, Retrieved from the Internet: URL:<a href="https://www.researchgate.net/profile/M_R_Lakshmikantha/publication/305046268_Fault_stability_assessment_for_well_planning_a_case_study_related_to_salt_structures/links/5780357908ae01f736e4a3ca/Fault-stability-assessment-for-well-planning-a-case-study-related-to-salt-structures.pdf?origin=publication">https://www.researchgate.net/profile/M_R_Lakshmikantha/publication/305046268_Fault_stability_assessment_for_well_planning_a_case_study_related_to_salt_structures/links/5780357908ae01f736e4a3ca/Fault-stability-assessment-for-well-planning-a-case-study-related-to-salt-structures.pdf?origin=publication</a> [retrieved on 2017-09-11] the whole document paragraphs [03.2], [03.3] the pore pressure distribution has been assumed hydrostatic</p>	1
A	<p>WO 2015/124633 A1 (REPSOL SA [ES]; UNIV POLITÉCNICA DE CATALUÑA [ES]) 27 August 2015 (2015-08-27) figures 4-6,14</p>	1
A	<p>US 2015/292323 A1 (SHAHRI MOJTABA P [US] ET AL) 15 October 2015 (2015-10-15) figure 9 the whole document</p>	1
A	<p>I Hossam ET AL: "Modeling and Validation of Fluid Flow-Geomechanics of Mauddud Reservoir in Sabriya Field* Search and Discovery Article #41052 (2012)**", 22 October 2012 (2012-10-22), XP055405343, Retrieved from the Internet: URL:<a href="http://www.searchanddiscovery.com/documents/2012/41052hossam/ndx_hossam.pdf">http://www.searchanddiscovery.com/documents/2012/41052hossam/ndx_hossam.pdf</a> [retrieved on 2017-09-11] the whole document</p>	1
A	<p>WO 2013/119685 A1 (MI LLC [US]) 15 August 2013 (2013-08-15) the whole document</p>	1
	-/--	

## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2018/058487

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>V Mostafavi ET AL: "Model - Based Uncertainty Assessment of Wellbore Stability Analyses and Downhole Pressure Estimations",</p> <p>26 June 2011 (2011-06-26), XP055405647, Retrieved from the Internet:  URL:https://www.onepetro.org/download/conference-paper/ARMA-11-127?id=conference-paper/ARMA-11-127  [retrieved on 2017-09-12]  the whole document</p> <p style="text-align: center;">-----</p>	1
A	<p>US 2015/055438 A1 (YAN GONG RUI [CN] ET AL) 26 February 2015 (2015-02-26)  the whole document</p> <p style="text-align: center;">-----</p>	1

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No PCT/EP2018/058487
---

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2013112114 A1	01-08-2013	AU 2011385380 A1	17-04-2014
		BR 112014007856 A2	18-04-2017
		CA 2850482 A1	01-08-2013
		CN 103959100 A	30-07-2014
		EP 2748649 A1	02-07-2014
		MX 341248 B	09-08-2016
		US 2014246244 A1	04-09-2014
		WO 2013112114 A1	01-08-2013
-----			
WO 2015124633 A1	27-08-2015	EP 3108088 A1	28-12-2016
		US 2017059742 A1	02-03-2017
		WO 2015124633 A1	27-08-2015
-----			
US 2015292323 A1	15-10-2015	AU 2015243844 A1	27-10-2016
		CA 2945044 A1	15-10-2015
		EP 3129578 A2	15-02-2017
		US 2015292323 A1	15-10-2015
		WO 2015157394 A2	15-10-2015
-----			
WO 2013119685 A1	15-08-2013	AU 2013217086 A1	28-08-2014
		AU 2016238868 A1	27-10-2016
		CA 2863796 A1	15-08-2013
		CN 104204407 A	10-12-2014
		CO 7131395 A2	01-12-2014
		EA 201491485 A1	30-01-2015
		EP 2812531 A1	17-12-2014
		US 2015041120 A1	12-02-2015
		WO 2013119685 A1	15-08-2013
-----			
US 2015055438 A1	26-02-2015	CA 2920884 A1	05-03-2015
		EP 3036398 A1	29-06-2016
		US 2015055438 A1	26-02-2015
		WO 2015031177 A1	05-03-2015
-----			