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(54) HYDRAULIC FRACTURING

(75) Inventor: Brice Tanguy Alphonse Lecampion, Richmond (AU)

Correspondence Address:
MERCHANT & GOULD PC
P.O. BOX 2903
MINNEAPOLIS, MN 55402-0903 (US)

(73) Assignee: COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION, Campbell (AU)

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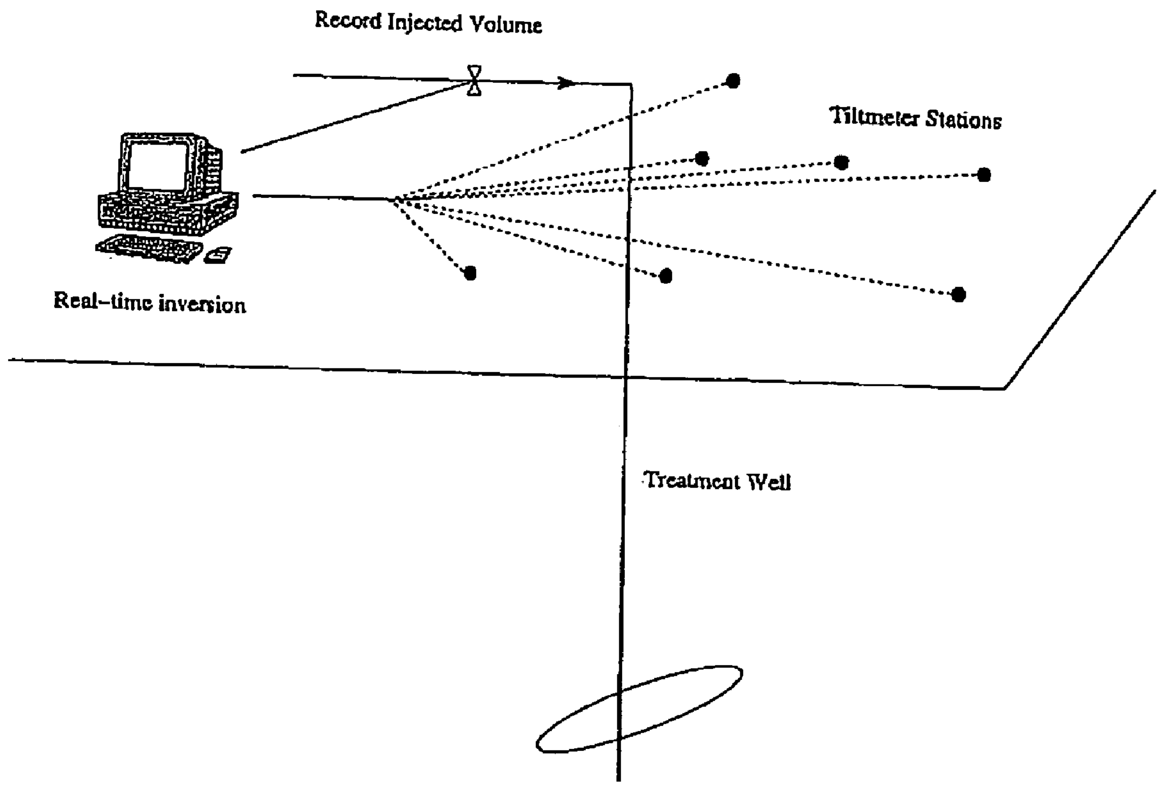
(57) ABSTRACT

Method and apparatus for monitoring growth of fracture during hydraulic fracturing treatment of a ground formation. A series of tiltmeters are positioned at spaced apart tiltmeter stations at which tilt changes due to hydraulic fracturing treatment are measurable by those tiltmeters. Tilt measurements obtained from the tiltmeters at progressive times during the fracture treatment are compared with estimated tilt changes estimated from an assumed hydraulic fracturing propagation. Useful values for initially undetermined values of parameters of the model are derived using an inverse procedure. The data analysis may be performed in real time as the hydraulic treatment progresses using differing propagation models to determine a most probable model.



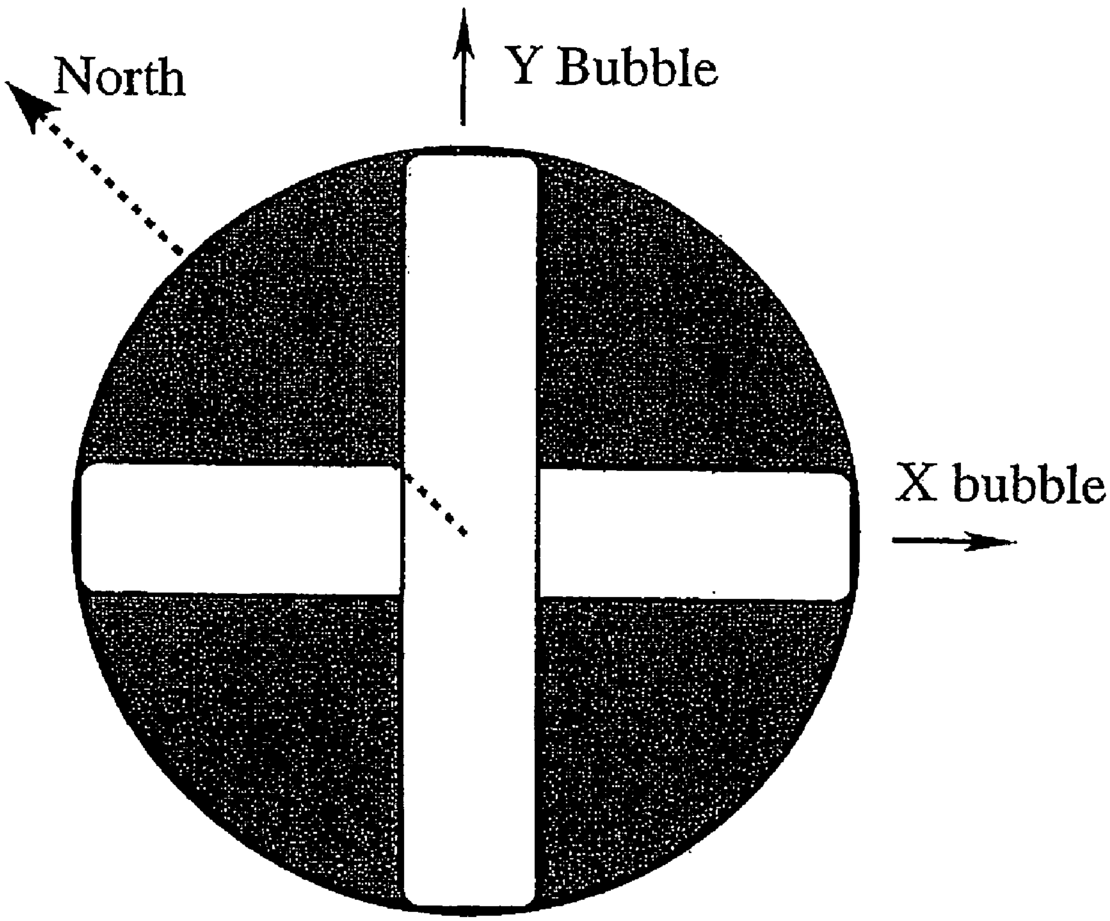


FIGURE 1

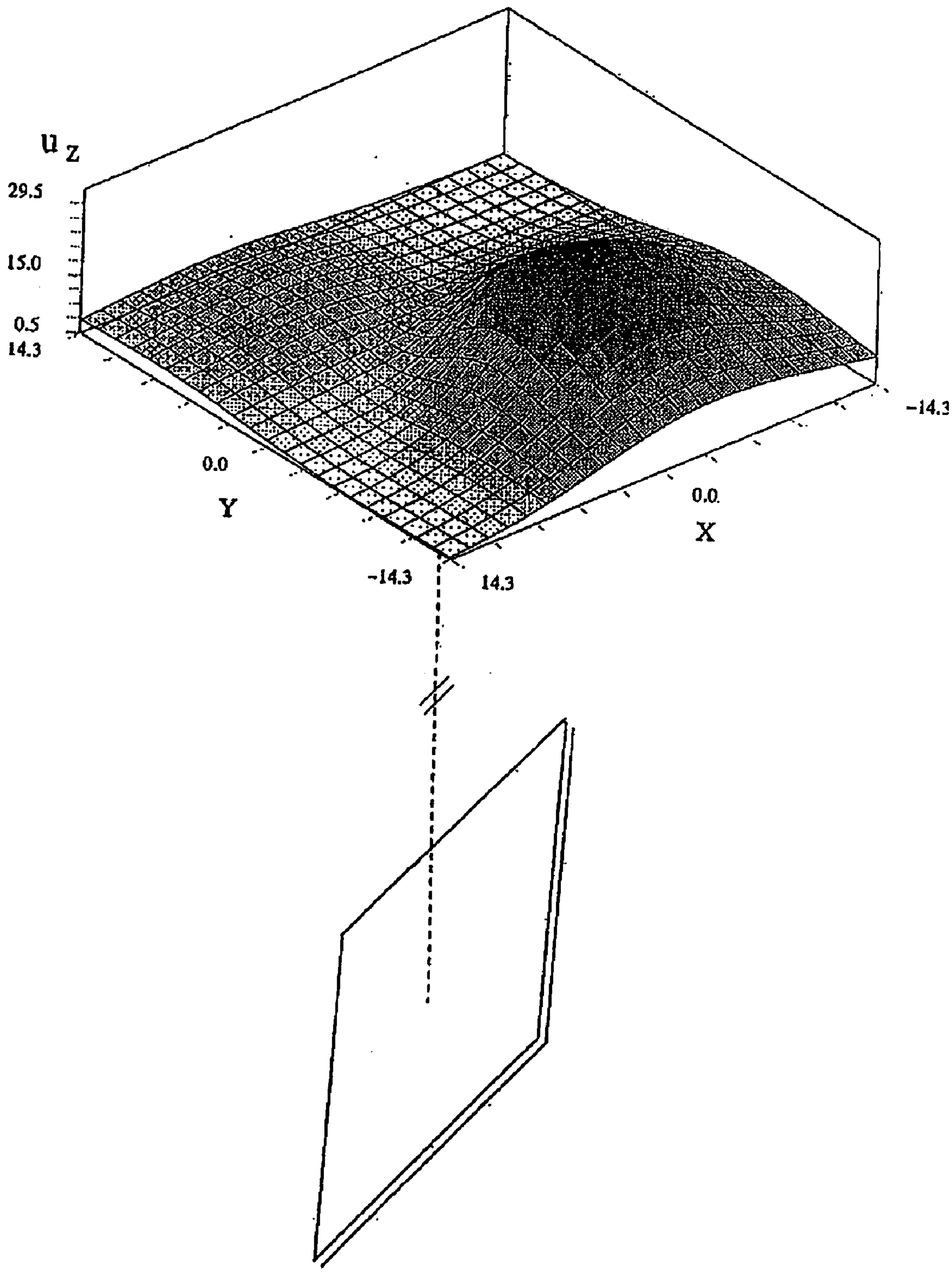


FIGURE 2

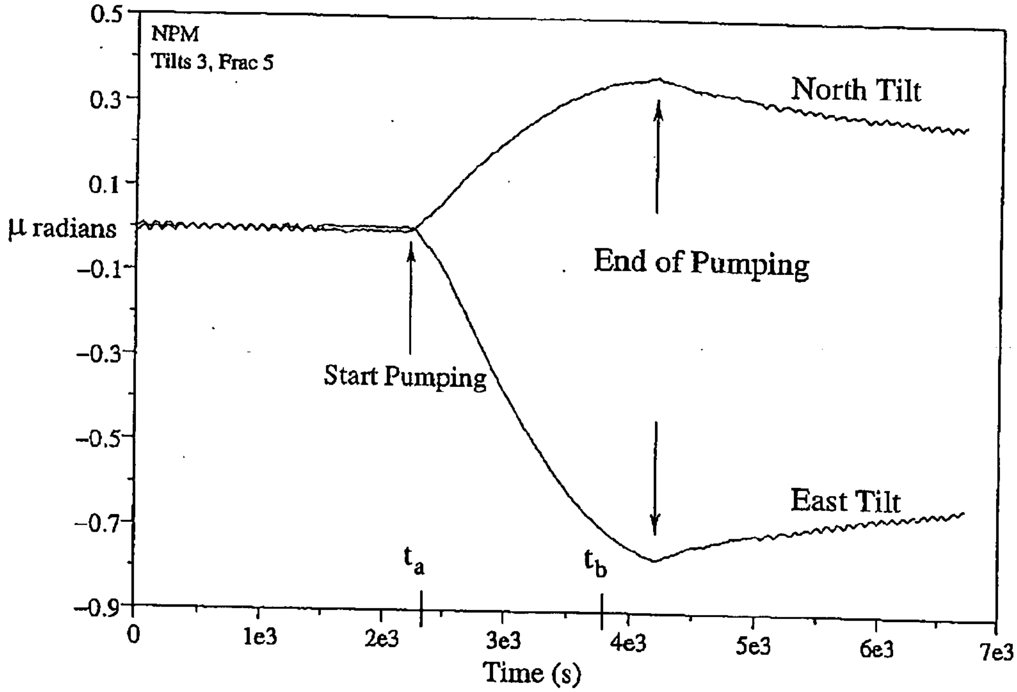

NPM
Tilts 3, Frac 5
North Tilt
End of Pumping
Start Pumping
East Tilt
μ radians
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
t_a
t_b
0
1e3
2e3
3e3
4e3
5e3
6e3
7e3
Time (s)

FIGURE 3

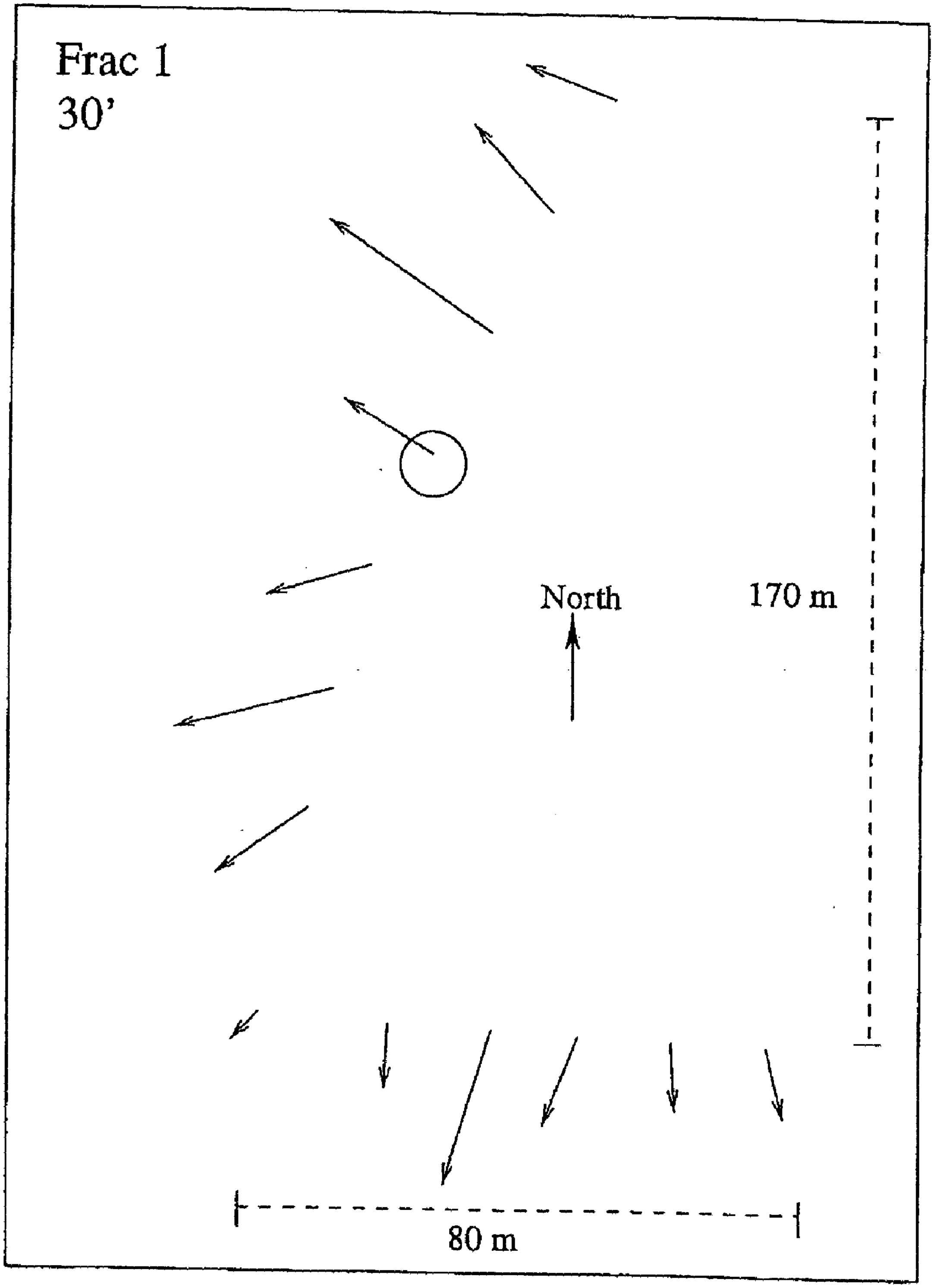


FIGURE 4

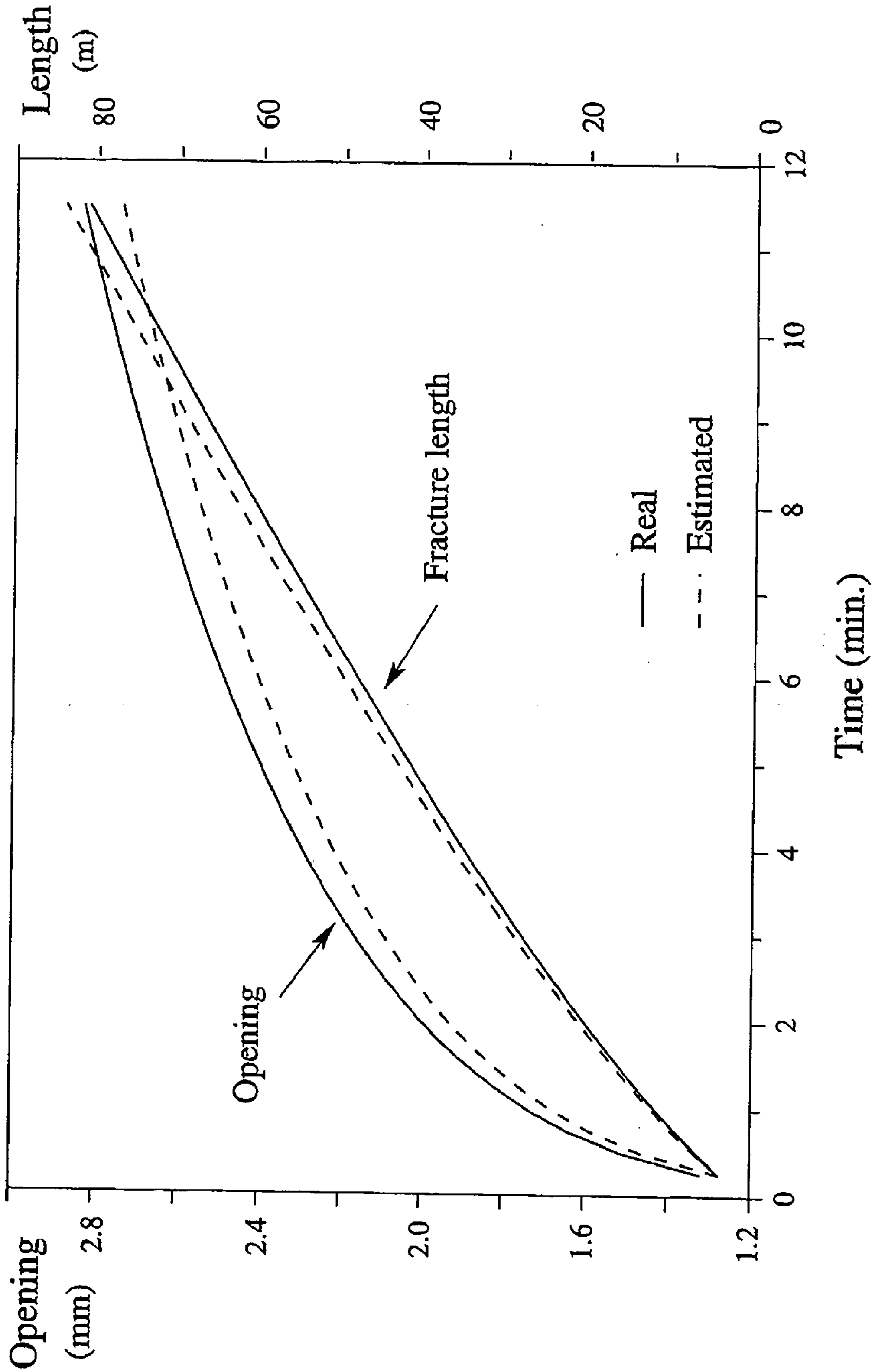

Length
(m)
80
60
40
20
0
Opening
(mm)
2.8
2.4
2.0
1.6
1.2
0
2
4
6
8
10
12
Time (min.)
Fracture length
Opening
Real
Estimated

FIGURE 5

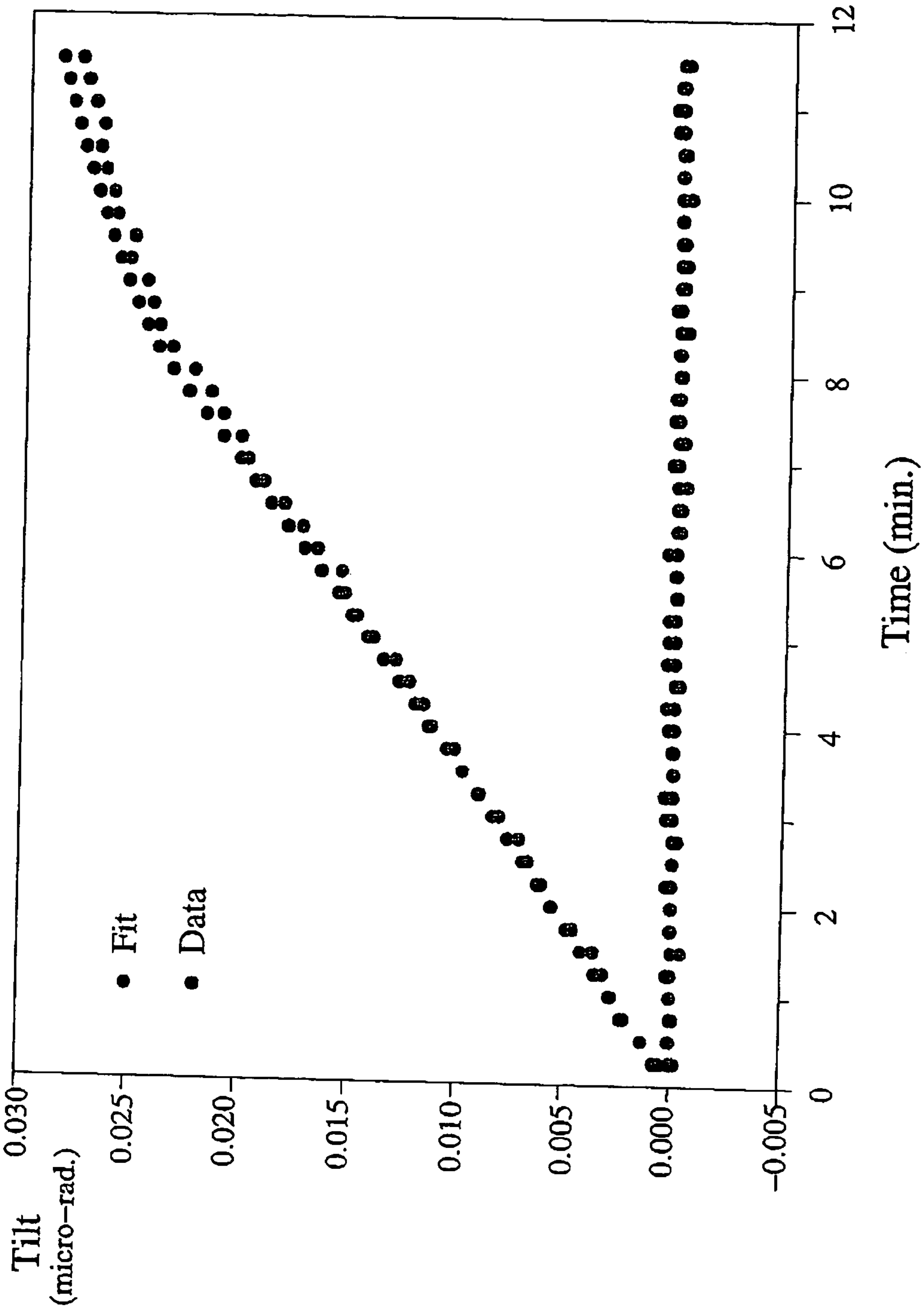

Tilt
(micro-rad.)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
-0.005
Fit
Data
0
2
4
6
8
10
12
Time (min.)

FIGURE 6

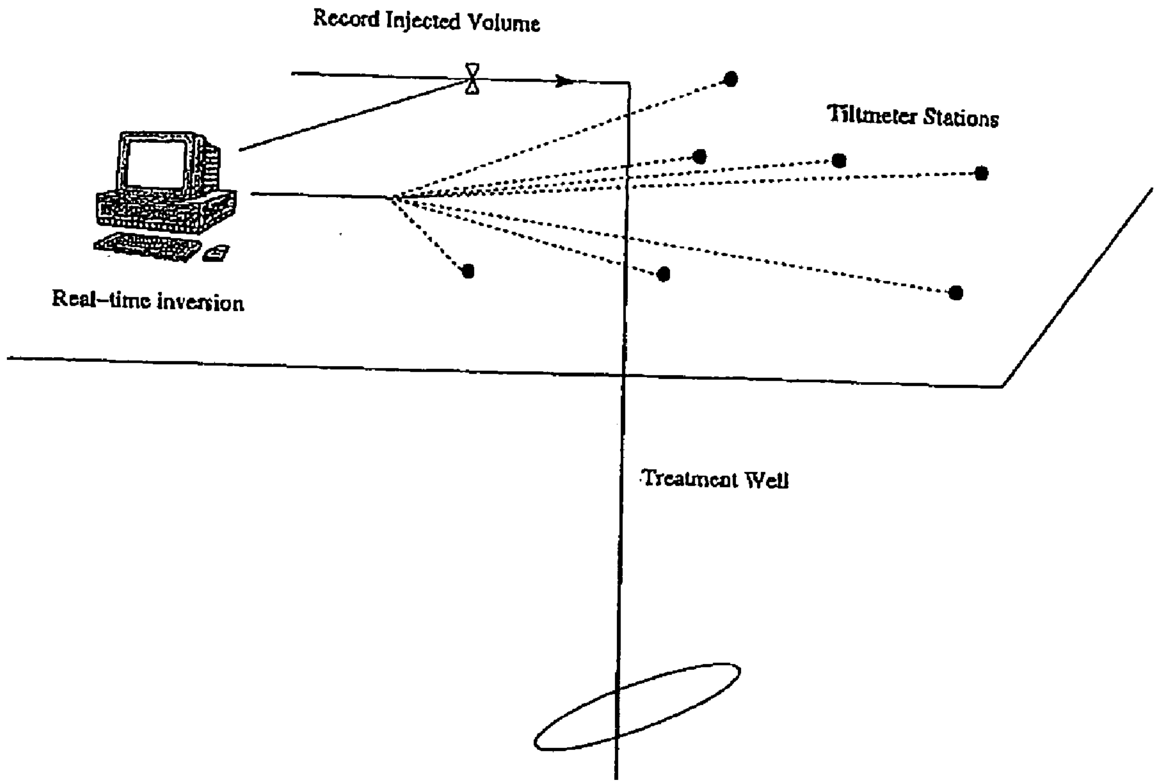

Record Injected Volume
Tiltmeter Stations
Real-time inversion
Treatment Well

FIGURE 7

HYDRAULIC FRACTURING

TECHNICAL FIELD

[0001] This invention relates to hydraulic fracturing of natural ground formations which may be on land or under a sea bed.

[0002] Hydraulic fracturing is a technique widely used in the oil and gas industry in order to enhance the recovery of hydrocarbons. A fracturing treatment consists of injecting a viscous fluid at sufficient rate and pressure into a bore hole drilled in a rock formation such that the propagation of a fracture results. In later stages of the fracturing treatment, the fracturing fluid often contains a proppant, typically sand, so that when the injecting stops, the fracture closes on the proppant which then forms a highly permeable channel (compared to the permeability of the surrounding rock) which may thus enhance the production from the bore hole or well.

[0003] In recent years, hydraulic fracturing has been applied for inducing caving and for preconditioning of rock for caving in the mining industry. In this application, the fractures are typically not propped but are formed to modify the rock mass strength and weaken the ore or country rock.

[0004] One of the most important issues in the practice of the hydraulic fracturing technique is knowledge of the geometry (orientation, extent, volume) of the created fracture. This is of particular importance in order to estimate the quality of the treatment performed. However, operators presently have only limited direct measurement capability that allows them to verify the quality and effectiveness of their operations. It is only afterwards when production has restarted that the performance of the created fracture can be assessed.

[0005] In order to map hydraulic fractures, several types of indirect measurements can be carried out such as microseismic acoustic monitoring and tiltmeter mapping, but until recently such surface tiltmeter techniques have not been capable of producing accurate real time information which can be used during the course of a hydraulic fracturing treatment and have generally been used to provide data for later analysis. However, our International Application PCT/AU2004/001263 discloses a method and apparatus whereby it is possible to obtain useful data on the effectiveness of a hydraulic treatment as the treatment progresses.

[0006] In accordance with the invention disclosed in PCT/AU2004/001263, tilt measurements may be obtained at spaced apart tiltmeter stations at progressive times during the fracturing treatment and a fluid driven fracture volume derived from those measurements by performing an analysis at each of those times as the treatment is in progress. The analysis may be based on minimisation of misfit between the tilt measurements at each given time and tilt predicted by a fracture model, for example a displacement discontinuity model.

[0007] The present invention involves an alternative kind of analysis which can be performed from tiltmeter or other data recorded during an interval of the fracturing treatment. Rather than analysing the data sequentially at different times independently, analysis in accordance with the present invention is carried out using data over an extended time interval, for example, the complete treatment time. By the present invention, it is possible to use a hydraulic fracturing propagation model to analyse the growth of the fracture through the time interval during which the relevant data is recorded and to use the recorded data to calibrate the model. The recorded data may be tiltmeter data, but it is possible to measure other data such as fracturing fluid injection pressure and acoustic emissions to constrain the growth model.

DISCLOSURE OF THE INVENTION

[0008] The invention broadly provides a method of monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

[0009] measuring at progressive times through an extended time interval during the treatment values of physical variables dependent on propagation of the fracture;

[0010] estimating, from an assumed hydraulic fracturing propagation model that is reliant on initially undetermined parameters, values of the variables at said progressive times through the extended time interval for differing values of said parameters; and

[0011] comparing the estimated values of said variables with the measured values to derive useful values of said parameters.

[0012] More specifically, the invention may provide a method of monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

[0013] positioning a series of tiltmeters at spaced apart tiltmeter stations at which tilt changes caused by the hydraulic fracture growth are measurable by those tiltmeters;

[0014] estimating, from an assumed hydraulic fracturing propagation model, tilt changes at the tiltmeter stations at progressive times through an extended time interval during the treatment;

[0015] obtaining, from the tiltmeters, tilt measurements at said progressive times throughout the extended time interval; and

[0016] comparing the estimated tilt changes through said time interval with the actual tilt measurements throughout that time interval.

[0017] The method may further comprise deriving from the comparison of the estimated and actual tilt changes useful values for initially undetermined values of parameters of the model.

[0018] The useful values of said parameters may be estimated using an inverse procedure.

[0019] Furthermore, other measurements such as recorded injection pressure, or/and acoustic emissions may be used to constrain the growth model if such measurements are available.

[0020] The method may also comprise the steps of:

[0021] estimating from one or more alternative hydraulic fracturing propagation models tilt changes at the tiltmeter stations at said progressive times throughout said time intervals;

[0022] comparing the estimated tilt changes estimated from the assumed and alternative propagation models with the actual tilt measurements to determine a most probable propagation model.

[0023] The comparison of estimated tilt changes with measured tilt changes may be performed in real-time as the hydraulic fracturing treatment progresses. For example, comparisons may be made from a first time interval from a start time and sequentially through successive longer time intervals from the same start time.

[0024] The invention also provides apparatus for monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

[0025] instruments to measure physical variables dependent on propagation of the fracture; and

[0026] a signal processing unit to receive measurement signals from the instruments at progressive times through an extended time interval during the fracturing treatment are operable to estimate from an assumed fracturing propagation model that is reliant on initially undetermined parameters, values of said physical variables at said progressive times through the extended time interval for differing values of said parameters and by comparison of the estimated values with the measurement signals to derive useful values of said parameters.

[0027] The invention further provides apparatus for monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

[0028] a series of tiltmeters positionable at spaced apart tiltmeter stations to measure tilt changes due to hydraulic fracturing treatment; and

[0029] a signal processing unit to receive tilt measurement signals from the tiltmeters at progressive times through an extended time interval during the fracturing treatment and operable to estimate from an assumed hydraulic fracturing propagation model tilt changes at the tiltmeter stations at progressive times through an extended time interval during the treatment and to compare the estimated tilt changes through said time interval with said tilt measurement signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The invention and the manner in which it may be put into effect will now be described in more detail with the aid of the references listed at the end of this specification and the accompanying drawings, in which:

[0031] **FIG. 1** illustrates the principle of tiltmeter measurement;

[0032] **FIG. 2** illustrates diagrammatically a dipping fracture and corresponding uplift at the ground surface;

[0033] **FIG. 3** illustrates the evolution in time of the inclination recorded at a tiltmeter station during a fracturing treatment;

[0034] **FIG. 4** illustrates tilt vectors at an array of tiltmeter stations at a particular instant of time during a fracturing treatment; and

[0035] **FIG. 5** shows the time evolution of the half-length of the fracture and opening of the fracture center of a PKN fracture growth model, both the correct (i.e simulated) value and the one obtained from the inversion of tilt data using the same fracture growth model are displayed,

[0036] **FIG. 6** displays the fit for the recorded tilts obtained from the inversion of a PKN fracture growth model;

[0037] **FIG. 7** displays a typical set-up to carry out the analysis in the field.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0038] In order to explain the operation of the preferred method and apparatus and according to the invention, it will be necessary to analyse in some detail the current state of the art in the operation of hydraulic fracture monitoring, especially tiltmeters, and the modelling and inverse techniques required to derive meaningful data from tiltmeter measurements.

Hydraulic Fracture Monitoring State of the Art

[0039] Several techniques have been developed in order to image hydraulic fracture. Three type of measurements are typically encountered in practice:

[0040] 1. well pressure monitoring

[0041] 2. passive seismic system recording acoustic emission during the fracturing process

[0042] 3. tiltmeters remotely located from the fracture measuring change of deformation as the fracture grows.

These methods have all their strength and weaknesses.

[0043] Well pressure monitoring is a simple measurement with a relatively low cost. When no pressure sensor is lowered down the injection well at the level of the injection interval, pressure is usually recorded on the surface rig together with the injected flow. In that case, corrections of the pressure drops due to viscous flow along the well have to be performed. The interpretation of well pressure with respect to hydraulic fracture growth can be rendered difficult due to damage around the well bore disturbing the fluid pressure gradients. Typical analysis of pressure decline, shut-in and fall-off data (G-plot etc.) can help estimating a number of characteristics of the fracture (treatment efficiency, closure stress etc.), Economides and Nolte, 2000 [5]. A number of simplifying assumptions are usually made in order to analyse pressure records.

[0044] Acoustic emission monitoring (also sometimes call passive seismic) consists of recording using precise accelerometers the seismic signal produced by the growth of the fracture. An array of geophones is used, and analysis of the signal enables to locate the seismic source. The velocity of seismic waves in the rock mass must be known. Usually, operators calibrate a velocity model by recording the signal generated by a known source (typically during the perforation of the casing). This method can provide good results in homogeneous rock mass if the array of sensor covers well the fracture area. In the case, where natural joints are present in the vicinity of the Hydraulic fractures, multiple shear events along the natural joints can occur. This can 'blur' the overall picture given by the analysis of the recorded signals.

[0045] A Tiltmeter (which is tightly installed in the rock) measures at its location changes of inclination in two orthogonal directions with a precision down to nanoradians. The tilts recorded are a direct measure of the small strain rotation at the apparatus location. In the field, tiltmeter fracture monitoring involves the deployment of a number of apparatus in the surroundings of the future fracture. Typically, they are either located on the surface of the earth in shallow boreholes (to minimize noise), or in an off-set well (downhole tiltmeter array), even sometimes the injection well itself (Davis, 1983 [4]; Evans, 1983 [7]; Branagan et al., [2]; Warpinski et al., [11]; Wright et al. [13]).

[0046] During a hydraulic fracture treatment, a measure of the different tiltmeters is recorded every 5 seconds or so, thus providing the effect of the fracture propagation on the elastic deformation field in the rock surrounding the fracture. **FIG. 4** displays for a given tiltmeter station, the two inclinations (north-south and east-west) recorded during a fracturing job. We clearly see the evolution of the inclination during the injection as well as the slow return toward their initial values after the end of the injection. This return is associated with the hydraulic fracture closing back on itself after injection stops. Another representation of tiltmeter measurements is given in **FIG. 5**. In case of a surface array, the so-called tilt vectors provide a spatial view (plan view) of the recorded inclination at the different tiltmeter station at a particular time during the injection. The tilt vector is determined from a vector addition of the two orthogonal components of the rotation tensor measured by the two bubbles in the tiltmeter:

$$v=\left(\frac{\partial u_z}{\partial x}-\frac{\partial u_x}{\partial z},\frac{\partial u_z}{\partial y}-\frac{\partial u_y}{\partial z}\right).$$

[0047] Such tiltmeter measurements are extremely precise and can furnish interesting data sets. In contrast to the relative simplicity of the measurement, the modelling necessary to quantitatively analyse tilt data pose difficult problems. Despite the now common use of tiltmeters to map hydraulic fractures in the petroleum industry, there is a widespread misunderstanding of what information about the fracture can and cannot be obtained from such measurements. Lecampion et al. [22] have shown that for measurement located at a distance twice the fracture characteristics length, tilt measurements only sense the effect of fracture volume and orientation. Such situation occurs in the field when the tiltmeters are too far from the fracture: we are in a case of so-called far-field tiltmeter mapping. The specification of our International Application PCT/AU2004/001263 discloses the use of a fundamental Displacement Discontinuity model by which it is possible to carry out a real-time analysis of the hydraulic fracture volume and the treatment efficiency, particularly for far-field tiltmeter mapping. The disclosure of that specification is imported here by reference.

[0048] If the tiltmeter are sufficiently close to the fracture, the fracture shape starts to affect the recorded tilts: this is a case of near-field tiltmeter mapping. In near-field tiltmeter mapping, the use of simple static fracture model (radial, elliptical, rectangular DD . . .) faces the problem that these models do not have the correct boundary conditions on the fracture face, which can results in doubtful conclusions.

New Analysis

[0049] By the present invention, an alternative method to analyse data recorded around hydraulic fractures is proposed. The method may use tiltmeter data but other data such as measurements of the injection pressure and acoustic emission can also be used. The method consists of coupling hydraulic fracture growth models (which model the physical process of Hydraulic fracturing either numerically or analytically depending on their assumptions) to the recorded data, and to calibrate the parameters of the hydraulic fracture growth models from the data. In contrast to existing methods, where data are analysed sequentially at different times independently, here the analysis is carried out using the data over an entire time interval and uses physical models of the HF process, not just static fracture models like the ones described in Warpinski 2000; [15]; Evans, 1983 [7]. Essentially the data recorded throughout the entire time interval are used in an inverse procedure to derive useful values for initially unknown values of parameters in the model. This will normally involve estimating data at the relevant time with differing assumed values of the parameters and comparing the various estimates with the recorded data to derive values which can then be used in the model to estimate evolution of the fracture.

[0050] The propagation of a hydraulic fracture is a highly non-linear process. Recent advances in the understanding of the key parameters controlling the growth of such fracture have shown that different regimes of propagation can be isolated (see Detournay, 2004 [17]; Adachi, 2001 [1]; Detournay et al. [18] for extensive discussions). The propagation of a hydraulic fracture is governed by two competing dissipative processes associated with fracturing fluid viscosity and rock toughness, respectively and two competing components of the fluid balance associated with fluid storage in the fracture and fluid storage in the surrounding rock (leak-off). Scaling laws as well as complete solutions for the propagation of hydraulic fractures have been recently obtained for simple fracture geometries such as a radial fracture and a plane strain fracture. This approach is useful for the design of HF treatment and has been described in reference [17]. Also, complex and computationally efficient numerical models are now becoming available (Siebrits, E. and Peirce, A. P.; 2001 [9]). We have also to note that empirical growth models are sometimes used in the industry for practical purposes [5]. All these hydraulic fracture growth models furnish a solution at all times during the injection period for the fracture shape, fracture aperture and internal fluid pressure (therefore well pressure) etc. everywhere in the fracture. Moreover, for a given fracture evolution, the corresponding tiltmeters at the different observation point and at the different time can be simply obtained from the solutions of an elasto-static problem (Eshelby, 1957 [6]) for each fracture configuration (i.e. each time). The location of seismic events obtained from acoustic emission can be qualitatively associated with the fracture front and the front of fluid leaking into the rock formation.

[0051] Typically, a particular fracture growth model depends on a number of parameters lumping physical properties of the rock, the layering structure, state of initial stress, the properties of the injected fluid driving the fracture as well as the pumping schedule. Some, if not all, of these parameters are often poorly known. Data recorded during the actual treatment can be used to back calculate these parameters. Moreover, several growth models with different type of assumptions can be tested against the data recorded.

Fracture Models

[0052] For example, we can suppose a simple PKN model for the fracture growth (see Economides and Nolte [5] for details). This is a typical model use in the industry for a vertical fracture growing in a confined layer. According to this model, the half-length of the fracture and fracture aperture at the fracture center evolves as:

$$l(t) = 0.68\left(\frac{E' Q_o^3}{2\mu H^4}\right)^{1/5} t^{4/5} = 0.68\alpha \times t^{4/5} \tag{1}$$

$$w(0, t) = 2.5\left(\frac{2\mu Q_o^2}{E' H}\right)^{1/5} t^{1/5} = 2.5\beta \times t^{1/5} \tag{2}$$

where E' is the plane strain, μ the fluid viscosity, H the layer in which the fracture is developing and Q_o the fluid injection rate (supposed constant). t denotes the time from the beginning of the injection. For that particular growth model, the unknown parameters will be

$$\alpha = \left(\frac{E' Q_o^3}{2\mu H^4}\right)^{1/5} \text{ and } \beta = \left(\frac{2\mu Q_o^2}{E' H}\right)^{1/5}.$$

[0053] Alternatively, we can assume that the created hydraulic fracture is radial and grows in the so-called toughness dominated regime (Detournay, 2004 [17]). When a Newtonian fracturing fluid is injected at a constant rate, the radius and net pressure inside the fracture evolves as power law of time:

$$R(t) = L_k \gamma_{ko}\left(\frac{t}{t_c}\right)^{2/5} \tag{3}$$

$$p(t) = \varepsilon_k E' \Pi_o\left(\frac{t}{t_c}\right)^{-1/5} \tag{4}$$

where

$$\gamma_{ko} = \left(\frac{2}{\pi 2^{1/2}}\right)^{2/5},$$

$$\Pi_{ko} = \frac{\pi}{8}\left(\frac{\pi}{12}\right)^{-1/5}$$

and the characteristic time t_c is related to the injection rate, plane strain Young's Modulus, fracture toughness and fracturing fluid viscosity:

$$t_c = \left(\frac{\mu'^{1/5} Q_o^3 E'^{13}}{K'^{18}}\right)^{1/2}$$

[0054] The characteristic lengthscale L_k and dimensionless number ϵ_k are given by (see Detournay, 2004 [17]):

$$\overline{L_k} = \frac{E'^3 Q_o \mu'}{K'^4}$$

$$\overline{\varepsilon_k} = \left(\frac{K'^6}{E'^5 Q_o \mu'}\right)^{1/2}$$

[0055] For that radial fracture toughness dominated growth model, the unknown parameters to be identified during the inverse analysis of the tilt series data are $\alpha = \overline{L_k}(t_c)^{-2/5}$ and $\beta = \epsilon_k(t_c)^{1/5}$.

Of course, more complex numerical models with a larger number of parameters can be used. Some parameters of the numerical simulation can also be isolated in order to be estimated in the inverse analysis.

Inversion

[0056] All the data from tiltmeters recorded during a time interval of the treatment can be used to perform an inverse calculations to estimates the parameters of a given growth models. Eventually, the parameters of several competing models can be estimated and the different models quantitatively ranked using a Bayesian model selection procedure as discussed in Raftery, 1995 [21]. It is therefore possible to detect the regime of propagation in which the hydraulic fracture is growing during that time interval.

[0057] Let us describe the inverse procedure. Consider a fracture growth model M, with parameters m=(α, β, etc . . .). For a given value of its parameter, this model furnishes the fracture shape S, aperture w and pressure p at all time. It is therefore possible to compute, for this value of the parameters, the tilts at all the tiltmeter location for all time where the tilts are sampled. We shall denote the predicted tilts (or eventually well pressure, or acoustic event location) as a function of the unknown parameters of the model: g(m).

[0058] If we have N tiltmeter stations, each recording two components of tilts, and p samples during the time interval for each stations, we have a data vector d of length 2*N*p.

[0059] The inverse procedure seeks to minimize the error between the predictions and the observation in order to obtain the best fit (Vogel, 2000 [10]; Tarantola and Valette, 1982 [19]):

$$J(m) = \frac{1}{2}\|g(m) - d\| \tag{5}$$

Prior knowledge on the parameters can be input in the procedure (see Tarantola and Valette, 1982 [19]; Ulrych T. J. et al. 2001 [20]). The minimization of the error can be done by using several methods (random search, Quasi-Newton Methods etc.). The best fit furnishes the best estimates for the model parameters. The knowledge of the best estimates of the model parameters allows to obtain the evolution of the fracture shape, aperture etc. during the injection period. The growth model is then calibrated.

An Example

[0060] As an illustrating example, let consider the following synthetic case. The tiltmeter data corresponding to the growth of a Hydraulic Fracture of so-called PKN geometry (with coefficients $\alpha=2$, $\beta=2e-3$, see eqns (1)-(2)) . . . are simulated and noise is added to this synthetic data set. The data are logged by a borehole array located 200 meters from the fracture (a far-field array). Tilts are sampled every minute. The synthetic data are then inverted using the same PKN model for the fracture growth model (see eqns. (1)-(2)). The parameters (α,β) are supposed unknowns and are retrieved via an inverse calculation using the simulated tilt data. The values of both parameters are retrieved accurately, we obtain $\alpha=1.94$, $\beta=1.98e-3$. The fit of the tilt data at a particular tilt station can be seen in **FIG. 6**. **FIG. 5** shows the time evolution fracture half-length and aperture at the fracture center obtained from eq. and the estimated values of the coefficients α and β. The estimated values of the model parameters allow to obtain fracture length and aperture.

Steps of the Analysis

[0061] As a guideline, the practical steps of the analysis are typically the following:

[0062] Collect data at all the tiltmeter stations for all sampling times during the interval of interest $t\in[t_a,t_b]$, correct the tiltmeter data (drift, earth tides, rotation to the geometrical coordinate system);

[0063] Perform the identification procedure for a particular fracture propagation model using the tilt data at the different instrument locations over the time interval of interest in order to estimate the model parameters; and

[0064] Eventually repeat the preceding step with a different propagation model and compare the different fracture propagation models.

[0065] We have to note that the computational speed of the models make it possible to carry out a real-time analysis, as described above, during the treatment. For example, the analysis can be performed on the first five minutes of the treatment, then on the first ten minutes of treatment and so on, eventually allowing design changes to be performed according to the calibrated model.

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1. A method of monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

measuring at progressive times through an extended time interval during the treatment values of physical variables dependent on propagation of the fracture;

estimating, from an assumed hydraulic fracturing propagation model that is reliant on initially undetermined parameters, values of the variables at said progressive times through the extended time interval for differing values of said parameters; and

comparing the estimated values of said variables with the measured values to derive useful values of said parameters.

2. A method as claimed in claim 1, comprising the further step of estimating from the assumed hydraulic fracturing propagation model and the derived useful values of said parameters future propagation dependent variables.

3. A method as claimed in claim 1, wherein the useful values of said parameters are derived by an inverse procedure.

4. A method as claimed in claim 3, wherein the inverse procedure is a Bayesian procedure.

5. A method as claimed in claim 1, wherein said physical variables comprise tilt changes measurable by tiltmeters disposed at spaced apart locations in the vicinity of the fracture.

6. A method as claimed in claim 1, wherein said physical variables comprise fracturing fluid injection pressure values.

7. A method as claimed in claim 1, wherein said physical variables comprise acoustic emissions data.

8. A method of monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

positioning a series of tiltmeters at spaced apart tiltmeter stations at which tilt changes caused by the hydraulic fracture growth are measurable by those tiltmeters;

estimating, from an assumed hydraulic fracturing propagation model, tilt changes at the tiltmeter stations at progressive times through an extended time interval during the treatment;

obtaining, from the tilmeters, tilt measurements at said progressive times throughout the extended time interval; and

comparing the estimated tilt changes through said time interval with the actual tilt measurements throughout that time interval.

9. A method as claimed in claim 8, further comprising deriving from the comparison of the estimated and actual tilt changes useful values for initially undetermined values of parameters of the model.

10. A method as claimed in claim 9, wherein the useful values of said parameters are derived using an inverse procedure.

11. A method as claimed in claim 10, wherein the inverse procedure is a Bayesian inversion procedure.

12. A method as claimed in claim 8, wherein the fracture orientation during said time interval is estimated from the tilt measurements.

13. A method as claimed in any one of claim 8, wherein measurements of data other than tilt changes are used to constrain the propagation model.

14. A method as claimed in claim 13, wherein said data include hydraulic injection pressure data.

15. A method as claimed in claim 13, wherein said data include acoustic emissions data.

16. A method as claimed in claim 8, wherein the comparison of estimated tilt changes with measured tilt changes is performed in real time as the hydraulic fracturing treatment progresses.

17. A method as claimed in claim 16, wherein comparisons are made through a first time interval from a start time and sequentially through successive longer time intervals from the same start time.

18. A method as claimed in claim 8, and comprising the steps of:

estimating from one or more alternative hydraulic fracturing propagation models tilt changes at the tiltmeter stations at said progressive times throughout said time interval;

comparing the estimated tilt changes estimated from the assumed and alternative propagation models with the actual tilt measurements to determine a most probable propagation model.

19. Apparatus for monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

instruments to measure physical variables dependent on propagation of the fracture; and

a signal processing unit to receive measurement signals from the instruments at progressive times through an extended time interval during the fracturing treatment and operable to estimate, from an assumed fracturing propagation model that is reliant on initially undetermined parameters, values of said physical variables at said progressive times through the extended time interval for differing values of said parameters and by comparison of the estimated values with the measurement signals to derive useful values of said parameters.

20. Apparatus as claimed in claim 19, wherein the signal processing unit is operable to derive the values of said parameters by an inverse procedure.

21. Apparatus for monitoring growth of a fracture during hydraulic fracturing treatment of a ground formation comprising:

a series of tiltmeters positionable at spaced apart tiltmeter stations to measure tilt changes due to hydraulic fracturing treatment; and

a signal processing unit to receive tilt measurement signals from the tiltmeters at progressive times through an extended time interval during the fracturing treatment and operable to estimate from an assumed hydraulic fracturing propagation model tilt changes at the tiltmeter stations at progressive times through an extended time interval during the treatment and to compare the estimated tilt changes through said time interval with said tilt measurement signals.

22. Apparatus as claimed in claim 21, wherein the data processing unit is operable to derive from the comparison of the estimated tilt changes and the tilt measurement signals useful values for initially undetermined values of parameters of the model.

23. Apparatus as claimed in claim 22, wherein the data processing unit is operable to derive the useful values of said dependent parameters by an inverse procedure.

24. Apparatus as claimed in claim 21, wherein the signal processing unit is operable to derive from the tilt measurements estimates of fracture orientation during said extended time interval.

25. Apparatus as claimed in claim 21, wherein the signal processing unit is operable to compare the estimated tilt changes with the tilt measurement signals in real time as the hydraulic fracturing treatment progresses.

26. Apparatus as claimed in claim 21, wherein the signal processing unit is operable to estimate from one or more alternative hydraulic fracturing propagation models tilt changes at the tiltmeter stations at progressive times throughout the extended time interval, and to compare the estimated tilt changes estimated from the assumed and alternative propagation models with the actual tilt measurement signals to determine a most probable propagation model.

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