US 20180066507A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2018/0066507 A1**

(43) **Pub. Date: Mar. 8, 2018**

Leach

(54) **ANALYSIS/VISUALIZATION OF A WELL DRILLING WINDOW**

(71) Applicant: **Colin Peter Leach**, Houston, TX (US)

(72) Inventor: **Colin Peter Leach**, Houston, TX (US)

(73) Assignee: **Mulberry Well Systems LLC**, Houston, TX (US)

(21) Appl. No.: **15/796,565**

(22) Filed: **Oct. 27, 2017**

Publication Classification

(51) **Int. Cl.**

E21B 44/00 (2006.01)

E21B 21/08 (2006.01)

(52) **U.S. Cl.**

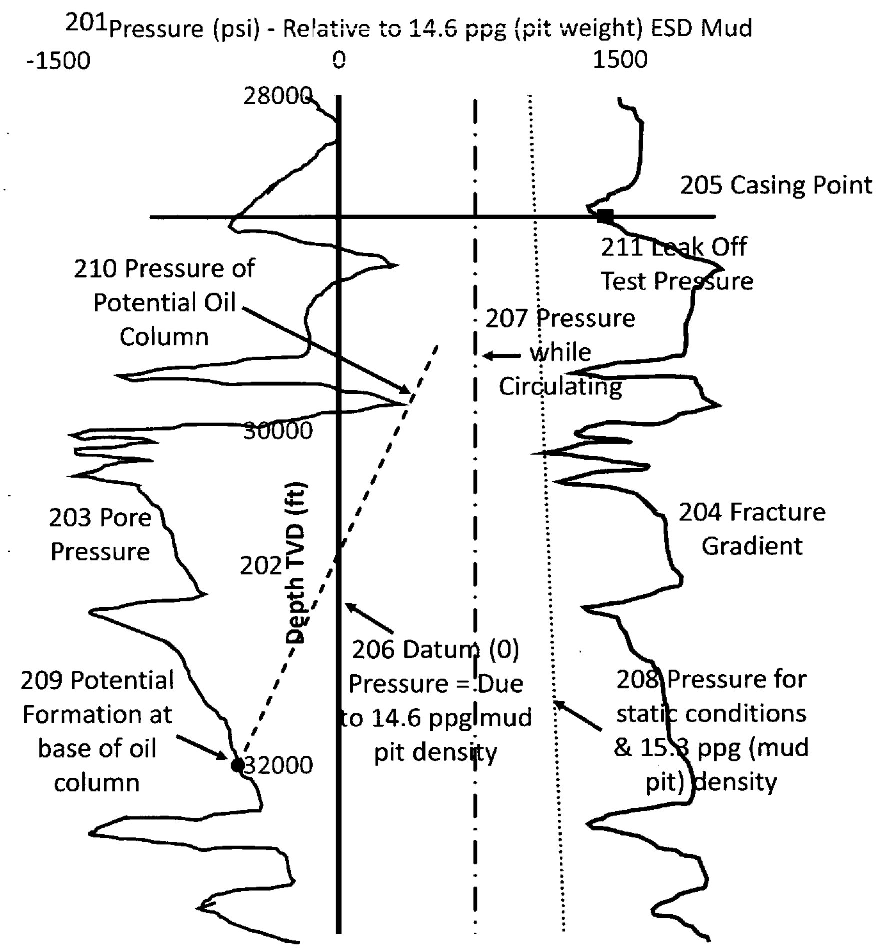
CPC ***E21B 44/00*** (2013.01); *E21B 47/04* (2013.01); ***E21B 21/08*** (2013.01)

(57) **ABSTRACT**

A way to analyze/visualize the options available to safely and effectively drill an oil or gas well through a pore pressure/fracture gradient (drilling) window is presented. This method has not been previously recognized or developed and switches the focus from the traditional view using a pressure gradient (mud weight or density) to a view using pressure relative to the pressure that would be supplied by the mud weight that is in the well at a static condition (the baseline).

This analysis/visualization has many advantages. It is easy to integrate Managed Pressure Drilling Operations, Horizontal wells, information from logging while drilling tools and in a real-time environment allows for the impact of operational fluctuations to be readily assessed and modeled. It is also envisaged that this analysis/visualization will enable regulatory authorities to better assess the safety of well operations reinforcing their ability to influence safe and effective drilling.

Analysis/Visualization of Drilling within a Small Window - General



All pressures are relative to the Datum Pressure

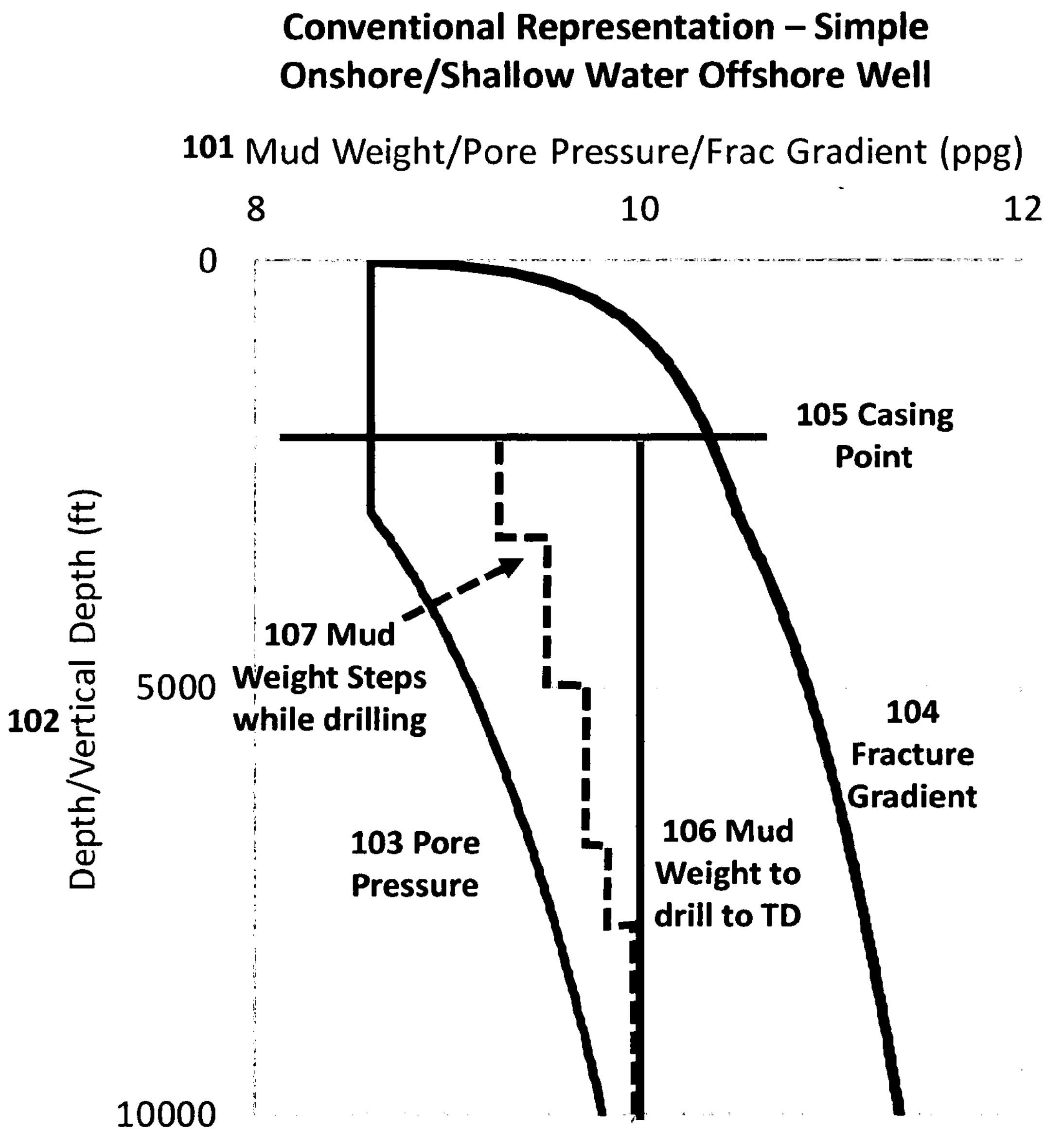

Conventional Representation – Simple
Onshore/Shallow Water Offshore Well
101 Mud Weight/Pore Pressure/Frac Gradient (ppg)
8
10
12
0
5000
10000
102 Depth/Vertical Depth (ft)
105 Casing Point
107 Mud Weight Steps while drilling
104 Fracture Gradient
103 Pore Pressure
106 Mud Weight to drill to TD

Fig 1

Analysis/Visualization of Drilling within a Small Window - General

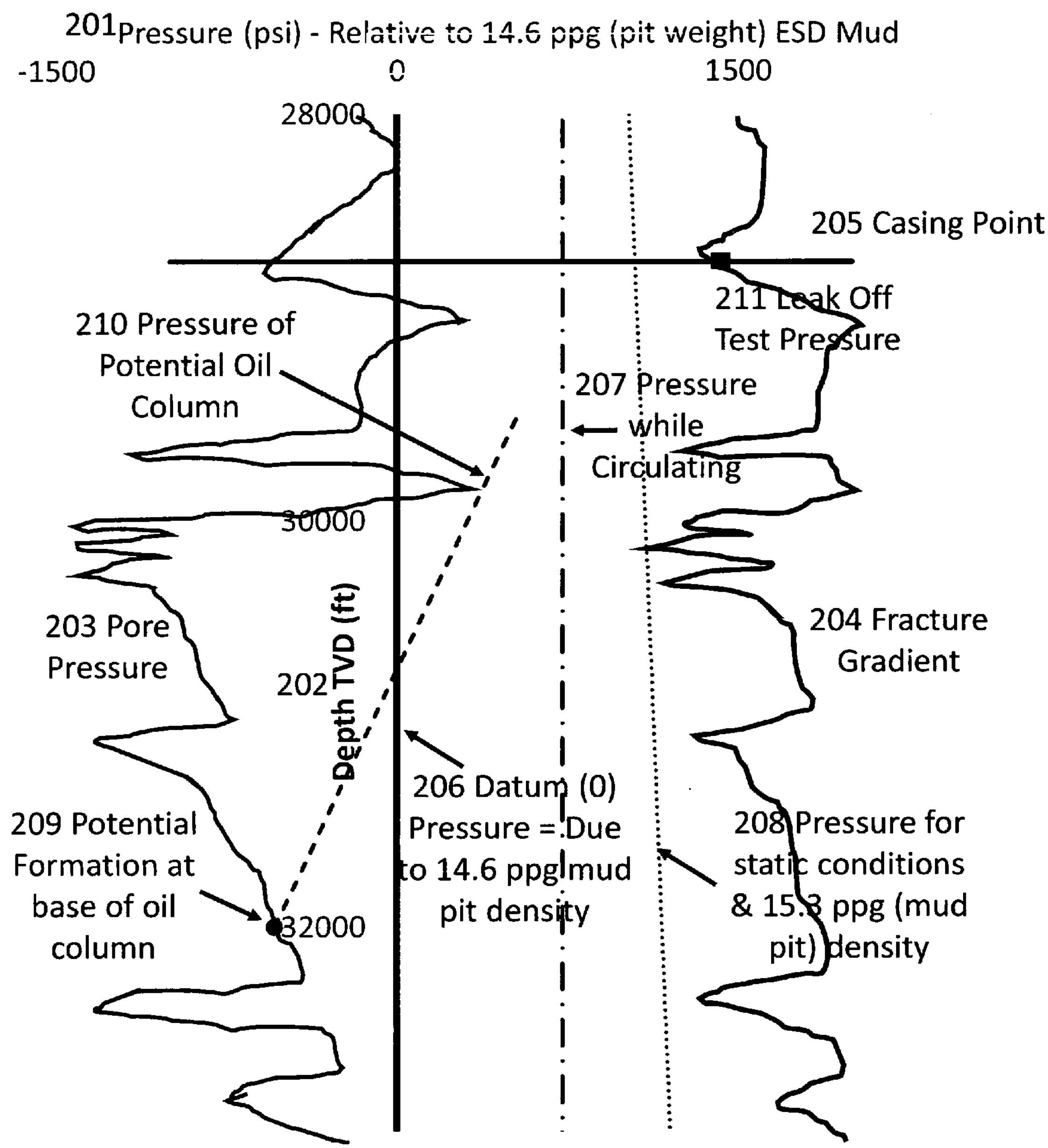


Fig 2 All pressures are relative to the Datum Pressure

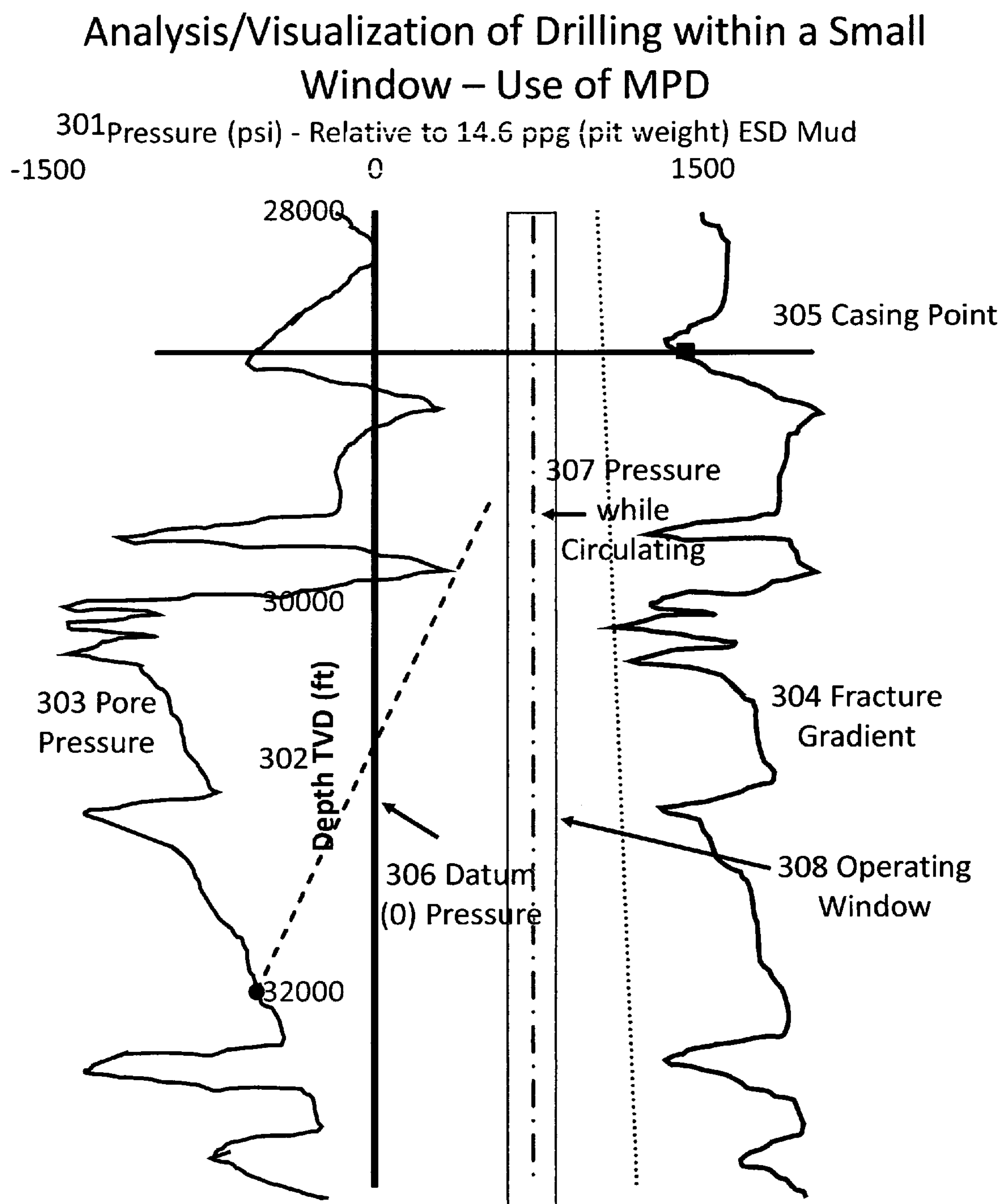


Fig 3 All pressures are relative to the Datum Pressure

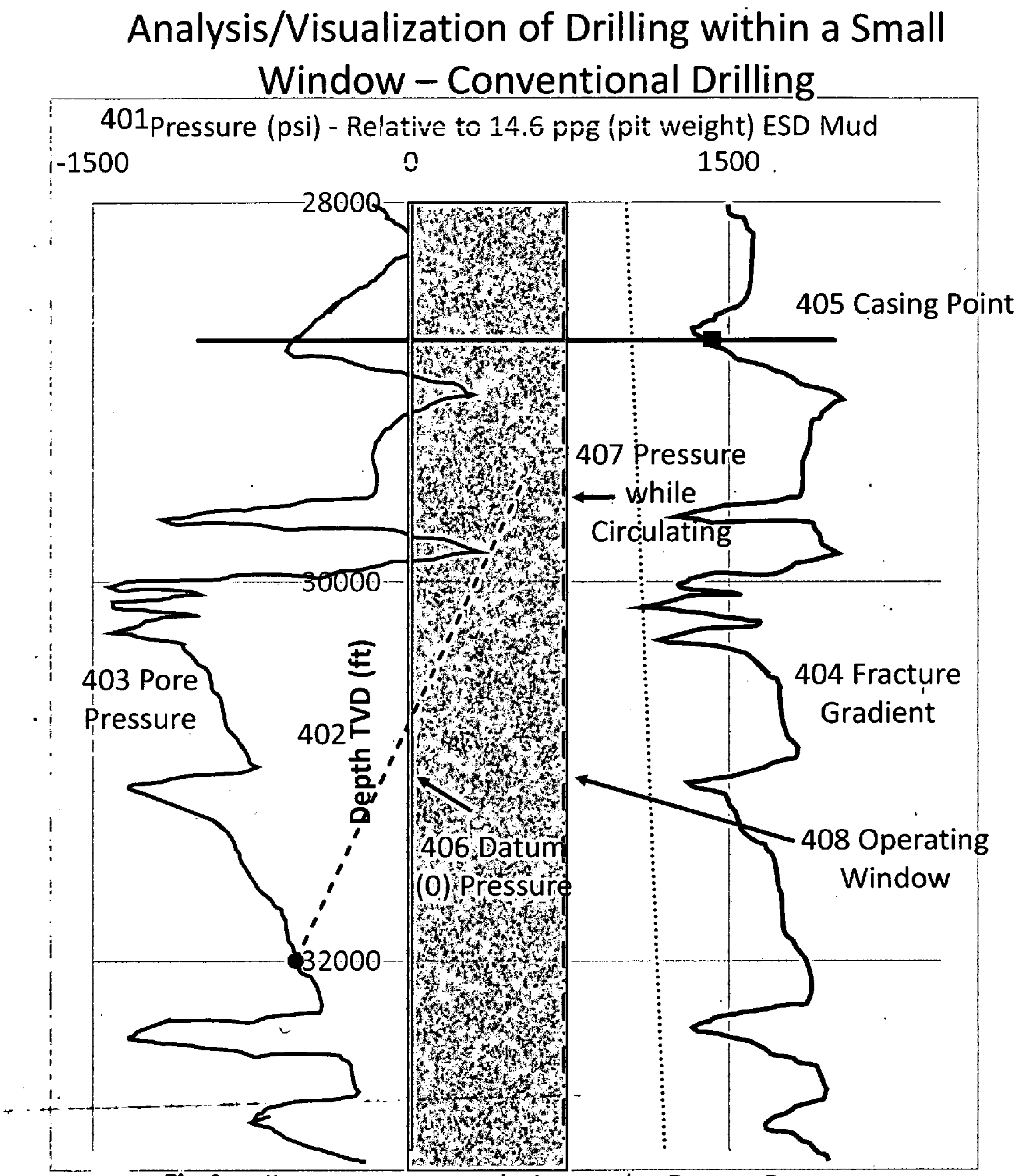


Fig 4 All pressures are relative to the Datum Pressure

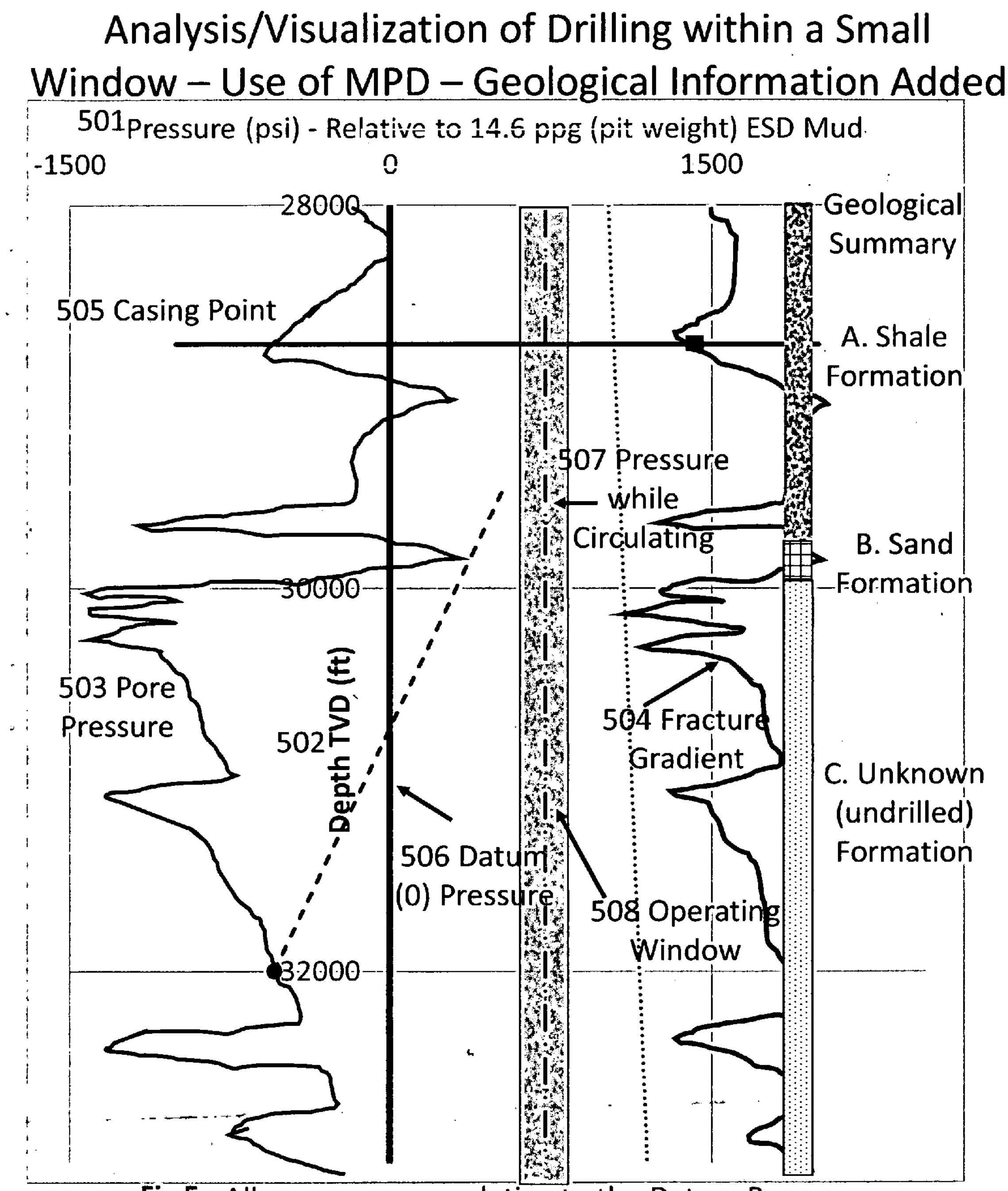


Fig 5 All pressures are relative to the Datum Pressure

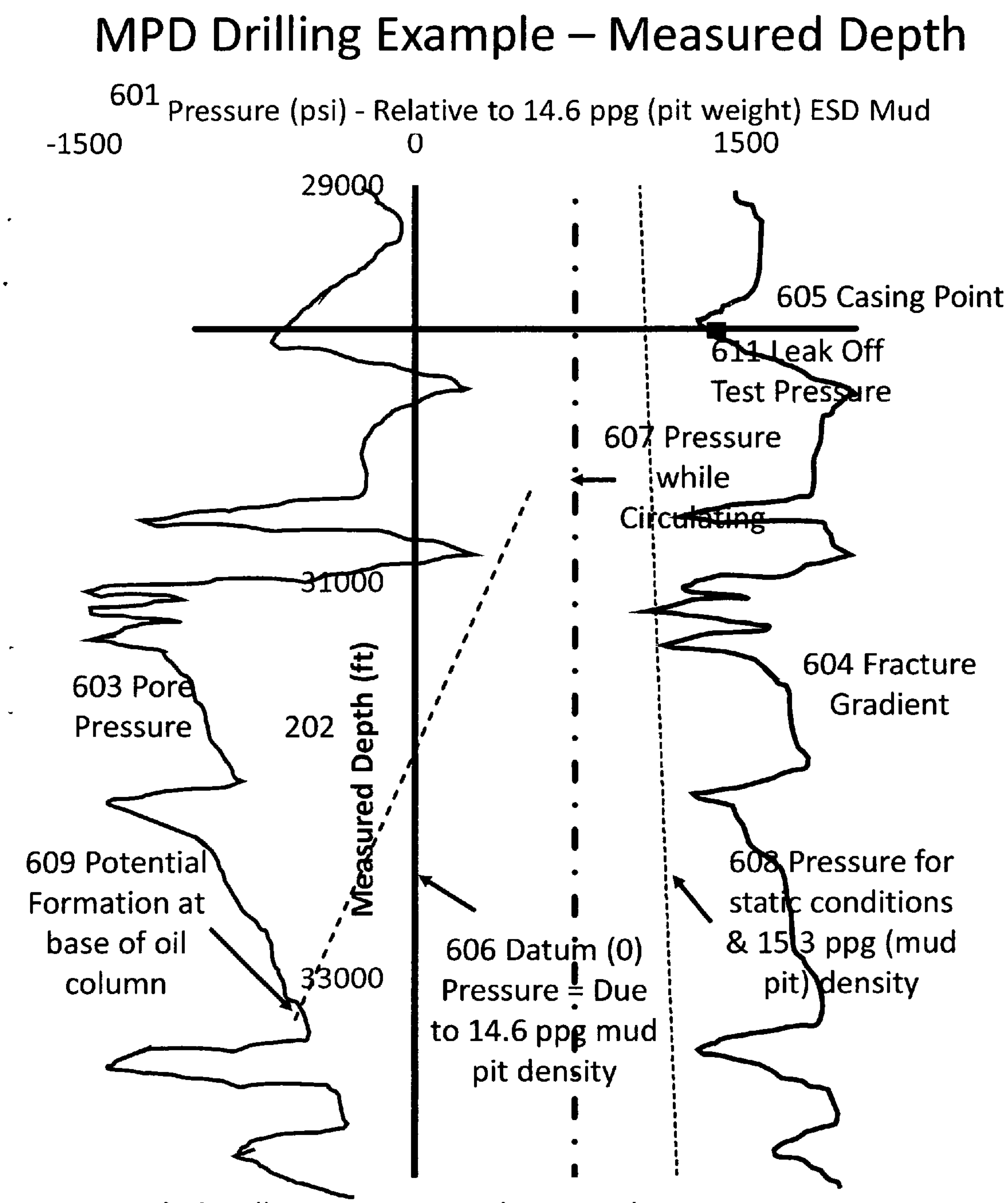


Fig 6 All pressures are relative to the Datum Pressure

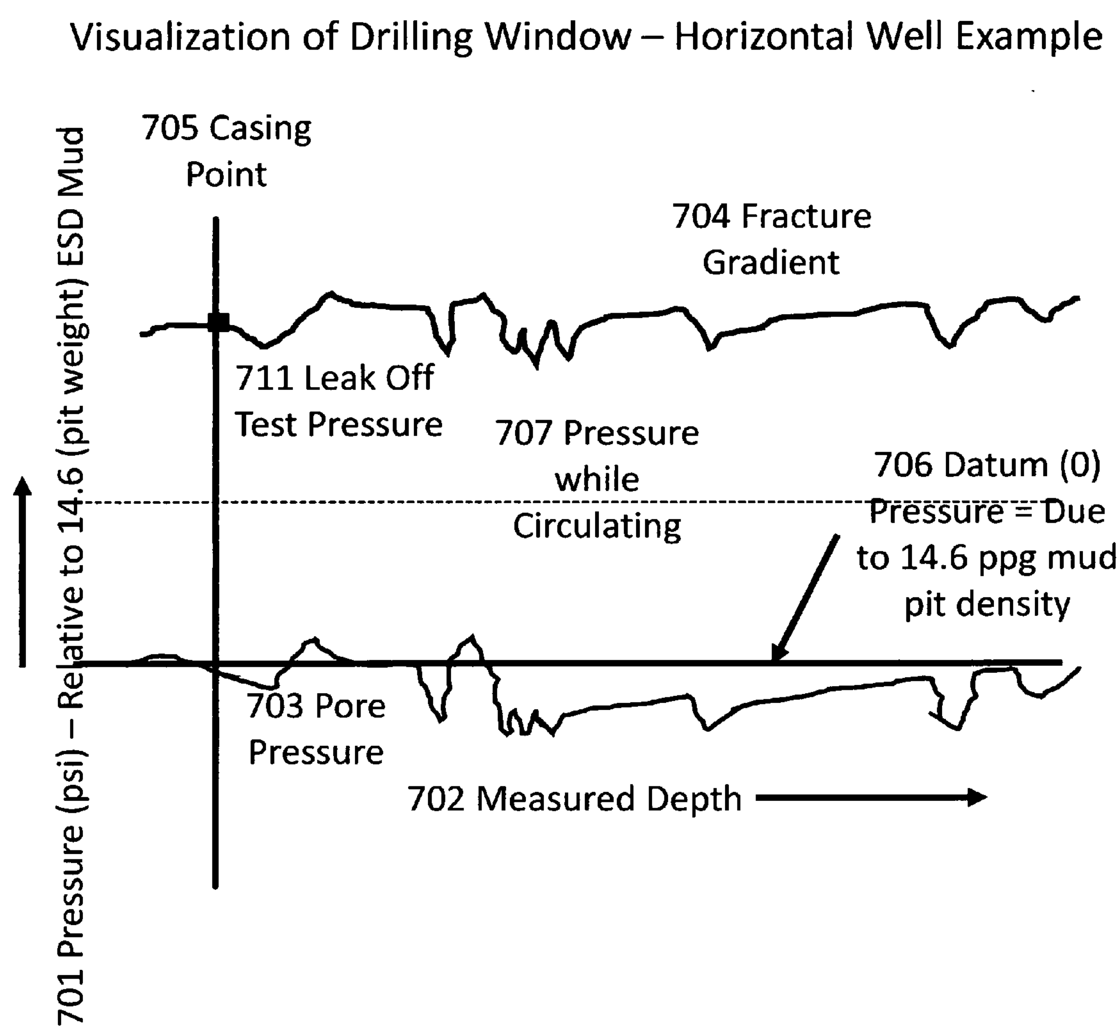


Fig 7 All pressures are relative to the Datum Pressure

ANALYSIS/VISUALIZATION OF A WELL DRILLING WINDOW

BACKGROUND OF THE INVENTION

[0001] Drilling mud has been used since the days of Spindletop (1901). The use of the mud density as the relative measure of the pressures within the well dates from the 1920s. This was appropriate and has served the (drilling) industry well in the intervening years. An "open" drilling system was used from this early period until quite recently. For this "open" drilling system, the only method of changing the pressure at the bottom of the well while drilling was to increase or decrease the mud weight. FIG. **1** shows a simple depiction of this approach. Units common to the USA are used. Other unit systems (e.g. Metric) are perfectly applicable to this "oilfield" approach.

[0002] The example in FIG. **1** is used to bring out how successful this approach has been but also its limitations. The key components of this diagram are:

[0003] **101** x-axis is mud weight (or density) measured in pounds per gallon (ppg) and typically measured near the mud pit using a simple mud balance

[0004] **102** y-axis is the well vertical depth (ft)

[0005] **103** is the pore (formation) pressure measured as a pressure gradient (ppg)

[0006] **104** is the formation fracture strength measured as a pressure gradient (ppg)

[0007] Note that for this simple well, there is a reasonable "window" between these two values (**103** and **104**). Current "rule of thumb" and US BSEE (Bureau of Safety and Environmental Enforcement) guidelines suggests that the margin between the well pressure (due to the mud density **106**) and fracture gradient (**104**) be a minimum of 0.5 ppg.

[0008] **105** shows the casing point. In this example, casing is set at 3000 ft vertical depth.

[0009] **106** shows the maximum mud weight (density) used in this well to reach Total Depth. In this example it equals 10.0 ppg (measured in the mud pits and assumed throughout the length of the well)

[0010] **107** shows how it is likely that the mud weight will be gradually increased as drilling progresses. The mud weight may be increased in steps or gradually increased as drilling continues.

[0011] The following is a summary of where the industry was at the time that that this mud weight/depth depiction was derived and developed.

[0012] (1) Many (historical) wells were drilled with water based mud (i.e. drilling mud containing gels and a weighting agent—typically barite) and with a 100% water based liquid phase. Given the temperatures and pressures encountered in these simple wells, the compressibility of this water based mud was negligible. As a result, downhole pressure could be represented by a very simple algorithm (given here in US units);

Downhole pressure (psi)=Mud Weight (ppg)×Vertical Depth (ft)×0.052 (conversion factor)

[0013] (2) Wells were drilled to fairly shallow depths (perhaps 10,000 ft maximum). As a result, the impact of "Annulus Friction Pressure" (also called Equivalent Circulating Density—ECD) was negligible. i.e. when the well was circulated (as opposed to when the well was static, the increase in Bottom Hole Pressure (BHP) due to the friction of the drilling mud in the annulus was small and could be effectively ignored.

[0014] (3) No effective means existed for the most part to increase the Bottom Hole Pressure upon the well except for increasing the mud weight. The advent of Managed Pressure Drilling (MPD) has been fairly recent.

[0015] (4) No means existed to be able to confirm the bottom hole pressure (Pressure While Drilling (PWD) became a reality in the late 1970's).

[0016] (5) Understanding of the formations encountered relied on interpretation of drilling rate, cuttings and gases circulated to surface.

[0017] (6) Most wells drilled in years gone by were fortunate to have a fairly large "drilling window" between pore pressure and fracture gradient. This meant that mud weights (i.e. downhole pressures) could be reasonably well above pore pressure and that many well incidents (such as pumping slugs of higher density muds etc.) would occur without exceeding the fracture gradient value which could result in lost circulation and significant drilling problems. Of course this sort of event did occur many times (often due to formation changes/unknowns, sometimes due to operational failures).

[0018] At this stage (2017) in drilling wells, the above factors have changed.

[0019] (1) Oil based muds (typically Synthetic Oil Based Mud (SOBM) are used in many wells. The compressibility (and hence density) of this mud varies significantly due to pressure and temperature and must be accounted for.

[0020] (2) Wells are often drilled to a much greater depth (perhaps to 30,000 ft or more). The "Annulus Friction Pressure" is significant and the difference between bottom hole pressure (pump on/pump off) cannot be ignored.

[0021] (3) Managed Pressure Drilling is now a mature option. Pressure can be added to the bottom hole pressure using additional surface (choke) pressure or by increasing the mud density (or both).

[0022] (4) PWD (Pressure While Drilling) now (since its early introduction in 1978) allows for confirmation of the Bottom Hole Pressure while drilling and the impact of operational changes upon this pressure.

[0023] (5) LWD (Logging While Drilling) now allows for interpretation of downhole formations in real-time (perhaps limited to 40-50 ft behind the bit) and for the ability to measure the potential producing formation pressures and properties without pulling the drilling string and running electric wireline and other logging tools.

[0024] (6) Many wells drilled today have very small drilling windows between pore pressure and fracture gradient in which to operate. From both a safety and efficiency perspective it is essential to be able to fully understand and utilize every bit of this window and know precisely where the operation fits within the boundaries.

[0025] The significant changes noted above suggest that it is time to change how we look at wellbore pressures. This is the subject of this invention. The key is that historically, practice has been to measure well pressures (in a gradient format) compared to the mud weight as measured in the mud pits. In the approach described here, the measurement is in absolute pressure terms, but in comparison to the pressure that is exerted on the well by a static column of mud taking into account the influence of temperature and pressure upon this column of mud. In turn this calculated/measured pressure (due to the static mud column) can be directly linked to a mud density measured (at a specific temperature) in the mud pits.

BRIEF SUMMARY OF THE INVENTION

[0026] The invention is a completely different way of analyzing/visualizing information used in the drilling of oil and gas wells. It enables the user to see and understand with great clarity the opportunities and the challenges/risks when drilling such wells.

[0027] The invention presented here requires that an understanding of the numerical impact of the invention is articulated. It is very difficult to achieve this using "non-numeric" examples. As a result, "numeric" examples are used. Given this, the analysis/visualization can be applied to all wells. The numeric impact will be different (and the resultant input to operational procedures etc. will be different), but the overall and specific application of the methods described here will be the same.

[0028] FIG. **2** shows the structure and some of the key capabilities of this analysis/visualization. By reading this section and with reference to the figure, the informed reader can understand the nature of the invention and the strengths of such an approach. The key components of FIG. **2** are:

- **[0029]** **201** x-axis is pressure measured in pounds per square inch (psi) relative to the zero (psi) datum which represents the pressure at any depth in the well due to the base mud measured in the mud pit (in this case 14.6 ppg—ESD Equivalent Static Density)
- **[0030]** **202** y-axis is the well vertical depth (ft). Note that Actual Measured Depth can be used instead. This is shown later.
- **[0031]** **203** is the pore (formation) pressure measured as a pressure (psi) relative to the base mud static pressure. Pore pressure estimations (prior to drilling) typically result in an absolute pressure versus vertical depth relationship.
- **[0032]** **204** is the formation fracture strength measured as a pressure (psi) relative to the base mud static pressure. Fracture pressure estimations (prior to drilling) typically result in an absolute pressure versus vertical depth relationship.

[0033] Note that for this challenging well, there is only a small "drilling window" between these two values (**203** and **204**). Current "rule of thumb" and US BSEE (US Bureau of Safety and Environmental Enforcement) guidelines suggests that the margin between the well pressure (due to the mud density **106**) and fracture gradient (**204**) be a minimum of 0.5 ppg. At a depth of 31000 ft, this would be effectively 806 psi.

- **[0034]** **205** shows the casing point. In this case, casing is set at about 28700 ft vertical depth.
- **[0035]** **206** shows the pressure datum line (0 psi) due to the (in this case) 14.6 ppg pit weight mud at the well depth. For the 31000 ft depth, the "simple" calculation of this pressure would be 23535 psi. In fact, the calculated pressure resulting from this pit mud weight (due to well pressure and temperature and the mud compressibility and confirmed by PWD measurement) is 23923 psi or 388 psi greater than the simple calculation. This new analysis/visualization accounts for this difference seamlessly.
- **[0036]** **207** shows the pressure (relative to the datum pressure) in the wellbore when the 14.6 ppg (mud pit measurement) mud is circulated at the drilling rate. In this case, the additional annulus circulating pressure is about 625 psi (it will vary slightly over the length of the well displayed).
- **[0037]** **208** shows the pressure (relative to the datum pressure) in the wellbore when the 14.6 ppg (mud pit measurement) mud is replaced by a 15.3 ppg (mud pit weight) mud. In this case, the additional pressure placed on the wellbore (relative to the 14.6 ppg mud pit mud) ranges from 1000 psi at 28000 ft to about 1200 psi at 33000 ft. Note that the relative pressure shown is for the static well case.
- **[0038]** **209** shows the potential pressure at the base of a potential oil column relative to the datum pressure.
- **[0039]** **210** shows the pressure (relative to the datum pressure) that a column of oil connected to the base of an oil column (**209**) would exhibit. Note that the (relative) pore pressure estimation shown is based on pressure in a shale column, hence pressure in a hydrocarbon filled sand column would be different and potentially as shown.
- **[0040]** **211** shows the result of a Leak Off Test relative to the datum pressure. This test is used to confirm the validity of the fracture gradient estimation.

[0041] FIG. **2** shows the capability of the approach and how much information can be displayed and communicated to the operations teams.

[0042] FIG. **2** does not include the use of Managed Pressure Drilling (MPD). For this method of drilling the most part the imposition of an additional small pressure (perhaps 100 psi) at one point in the wellbore (for example at the choke in a Managed Pressure Drilling system) will result in the same additional small pressure being imposed on other parts of the wellbore (for example bottom hole). In fact, the imposed pressure at this other point may be slightly different due to mud compressibility (for example), but this small (delta) difference can typically be ignored. This effect is sometimes termed "Superposition theory". The application for an MPD case is shown later.

BRIEF DESCRIPTION OF THE DRAWINGS

[0043] It should be noted that the figures provide examples of the approach, background etc. They do not depict real information from actual wells. This "real information" is in practice provided by in-depth pore pressure/fracture gradient studies, measurement and prediction of mud pressures and densities based on measured/predicted wellbore pressures and temperatures and other factors. This is not the subject of this patent document.

[0044] This analysis/visualization can be applied to any well. It is particularly useful for wells where there is a narrow operating widow, such as deepwater and High Pressure/High Temperature (HPHT) and those employing Managed Pressure Drilling (MPD).

[0045] FIG. **1** depicts the conventional/historical visualization of this data. This approach is commonly used and has been in use since the 1920s

[0046] FIG. **2** depicts the presentation (example) of the analysis/visualization of the pressures within a wellbore and in particular of the available drilling window.

[0047] FIG. **3** depicts this analysis/visualization when managed pressure drilling (MPD) is being used. The corresponding operating window requirement is narrow

[0048] FIG. **4** depicts this analysis/visualization when conventional drilling practices (without managed pressure drilling (MPD)) are being used. The corresponding operating window requirement is wide

[0049] FIG. **5** depicts this analysis/visualization when managed pressure drilling (MPD) is being used. A summary of geological formations drilled has been imposed upon the figure

[0050] FIG. **6** depicts this analysis/visualization using Measured Depth (as opposed to True Vertical Depth) as the y-axis

[0051] FIG. **7** depicts the information shown in FIG. **6** (modified to be more appropriate for a horizontal well), but with the axes swapped (i.e. Measured Depth is the x-axis and the Relative Pressure is shown on the y-axis). This is appropriate for a horizontal well

DETAILED DESCRIPTION OF THE INVENTION

[0052] In order to drill a well successfully without causing an uncontrolled flow of formation fluid from the well (also known as a blowout) or incurring massive lost circulation (whereby some control of the well can only be achieved by pumping a significant volume of fluid into the well) a pressure balance must be maintained whereby the pressure in the well and across any exposed formation must be greater than the pressure of any formation (which is capable of flow) exposed, but not so great that the pressure causes (a) an exposed formation to fracture resulting in loss of hydraulic control of the well and other potentially more serious problems or (b) significant fluid loss to an exposed low permeable low pressure formation.

[0053] As noted in the background, this control has been achieved historically based on measuring the density of mud in the mud pit (and hence the density of mud in the wellbore) and then comparing this mud density (weight) to the pore pressure and fracture gradient (expressed as pressure gradients in the same units as the mud density).

[0054] Simply put, this (historical) control approach is not precise enough for the difficult wells being drilled at this time. In addition, at this time we now have the capability of controlling pressure in the well by using mud density or by using a combination of mud density and pressure applied at the surface. It is also critical that other pressure losses in the system (for instance annulus friction pressure with the pump on) are accounted for and combined appropriately with the pressure resulting from the mud density column. The historical density/mud weight presentation does not allow for ready combination of pressure and density measurements or for the level of precision that is required.

[0055] Some companies have used a straight pressure (x-axis) versus vertical depth (y-axis) to represent this relationship. It indeed satisfies the precision required, but fails to provide the necessary communications to an operations team. For example (and at 31000 ft—see FIG. **1**), the pore pressure is 22923 psi, the pressure due to the mud density (static conditions) is 23923 psi and the fracture gradient (pressure) is 25048 psi. Whereas stating these values as is correct, it is not easy for an operations team to grasp the significance of differences.

[0056] (Note that by contrast in the (historical/conventional) approach, the corresponding pressure gradients would be 14.22 ppg, 14.84 ppg (different to the 14.6 ppg measured in the mud pit) and 15.54 ppg respectively)

[0057] What was needed was a pressure measurement, but one that was relative to one of the represented values. This datum represented value could have been chosen as the pore pressure, the pressure due to the static mud column or even the fracture gradient/pressure. It made most sense to choose the pressure due to the static mud column as this datum. The value of the pressure due to the mud column can be accurately calculated and confirmed using downhole measurements (PWD). The values of either pore pressure or fracture gradient are subject to uncertainty which will vary from well to well and on whether confirmation measurements have been made. Once this datum is chosen, other pressures can be calculated and displayed relative to this datum and a very clear picture obtained both of the existing well condition and what would occur if an operational input were altered.

[0058] This analysis/visualization is the same as the historical/conventional approach in that pressures (or for the historical/conventional approach pressure gradients) are expressed relative to a datum of the static mud in the well. This new approach completely changes the historical/conventional approach it replaces to include and allow for the complexity of the wells being drilled today and the significant information/data that is now available during the drilling operation.

[0059] This analysis/visualization is shown in FIG. **2**. For the example shown the content of the data lines included have been previously noted in the summary.

[0060] Note that the datum pressure is a 14.6 ppg (mud pit—ESD) weight mud. A second static mud weight (15.3 ppg mud pit (**208**)) has been added to show the effect that would occur if the mud weight were increased to 15.3 ppg (mud pit weight).

[0061] A pressure line representing the circulating condition that occurs with the 14.6 ppg (mud pit) weight mud is included (**207**). This includes approximately 625 psi of annulus circulating pressure (at the normal drilling pump rate). If a Managed Pressure Drilling (MPD) operation was used and 100 psi imposed as choke back-pressure during this assumed MPD operation the line (**207**) would simply be moved from 625 psi to 725 psi. This choke back-pressure can be readily altered. It can be seen that increasing this back-pressure could lead to the (**207**) line crossing the fracture gradient line (**104**) at a number of depths (particularly between 30000 ft and 30500 ft). The chart gives clear guidance that the imposed back-pressure should not be increased above a certain value.

[0062] In addition, it can be seen that the pressure of a potential large oil column (**209** and **210**) could exceed the datum pressure (**206**), but would be less than the circulating condition (**207**). If the pump is running and other actions are taken when the pump is turned off to maintain the wellbore pressure then the wellbore pressure can be maintained above this potential formation pressure and an influx avoided. Of course, if the pump is turned off and the wellbore pressure reverts to the static datum pressure (**206**) then there is the possibility of a formation fluid influx (a kick).

[0063] The analysis/visualization provides a very clear picture of these possibilities and allows for potential mitigating actions to be tested and then (if appropriate) carried out.

[0064] Note that estimations such as pore pressure (**203**) and fracture gradient (**204**) are (until data is gathered) just estimates, subject to uncertainty. The band of uncertainty around these estimates can be included upon the chart (not shown). In addition, estimates can be converted into known data once measurements are made and the choice of mud weight and choke back-pressure (and other parameters) re-assessed once this data is gathered.

[0065] FIG. **3** shows the same information as the example in FIG. **2**, but with an indication of the Operating Window Requirement (shown as a narrow shaded rectangle) for the case when Managed Pressure Drilling (MPD) is in use. In this case the difference in pressure between the situation where drilling is occurring and the drill pump is on and a choke back-pressure being maintained (**307**) and the situation where drilling is not occurring, the drill pump is shut down but an additional choke back-pressure being held is relatively small. For the duration of the drilling operation, the pressure at a point in the wellbore is almost constant, whatever the operation taking place is (unless a deliberate action has been taken to change this pressure).

[0066] FIG. **4** shows the exact same operation and conditions except that conventional (non-managed pressure drilling) operations are assumed. In this case an annulus friction pressure of 625 psi is applied in addition to the datum mud pressure (**406**) to generate a circulating pressure of (**407**) when the drilling pumps are on. When the drilling pumps are turned off (for example to make a connection), this annulus friction pressure (625 psi) is removed and the well pressure reverts to the datum mud pressure (**406**). When this occurs it is possible that a formation influx will occur at this time if the pore pressure (**403**) or the pressure of a potential oil column is high enough. There is a significant operating window requirement (shown as a wide shaded rectangle) (**408**).

[0067] The benefits of employing or not employing managed pressure drilling can readily be assessed using this analysis/visualization tool.

[0068] FIG. **5** shows the same information as shown in FIG. **3** (with MPD employed). An indication of the geological formations encountered (from LWD information) has been added—this would be carried out in real time. Given the underlying analysis/visualization graph, it can be readily seen that once a potential producing formation has been penetrated to a significant length it is appropriate to stop drilling and assess the actual pressure in this potential producing formation before drilling ahead and exposing the complete height of the producing formation. Action can then be taken to adjust the wellbore pressure such that in the future if an operational failure were to occur (for example failure of the MPD system), the consequences of such a failure can be handled. This is an example of how the analysis/visualization tool can be linked to a real time geological data feed to give the operations team a comprehensive understanding of (for example) both the pressures in the wellbore and the consequences of an interruption in the maintenance of wellbore pressure.

[0069] FIG. **6** shows the same information as FIG. **2**, but in this case, the y-axis contains actual Measured depths (ft) as opposed to True Vertical Depths (ft). The use of measured depth in this approach does not result in any complication as would its use in the historical/conventional approach.

[0070] In fact for horizontal wells, it may be appropriate to rotate the axes with the measured depth axis as the x-axis and the relative pressure axis as the y-axis. This is shown in FIG. **7**. Note that in practical terms the pore pressure and fracture gradient curves would likely be different and based on encountering different formations, depleted formations etc.

REFERENCES

[0071] (1) U.S. Pat. No. 6,871,532 (Zazovsky) Mar. 29, 2005—This patent recognizes the usefulness of a pore pressure relative to a baseline pressure (e.g that due to mud density), but does not develop or consider any aspects of the application of this relative measurement.

[0072] (2) U.S. Pat. No. 5,615,115 (Shilling) Mar. 25, 1997

[0073] (3) US 2011/0036587 (Pritchard et al) Feb. 17, 2011

[0074] (4) U.S. Pat. No. 8,347,983 B2 ((Hoyer et al) Jan. 8, 2013

[0075] (5) US 2016/0305231 (Majidi et al.) Oct. 20, 2016

[0076] References (2), (3), (4), and (5) above noted above illustrate increasingly more complex wells and wells in which more comprehensive methods of controlling bottom hole pressure are available. As with numerous other patents and published references, the relationship between the pressure imposed by the mud density and the pore pressure and fracture gradient are represented in a similar format to that illustrated in FIG. **1**.

1. An analysis/visualization of pressures existing and imposed within a wellbore during the drilling operation, such that the risks and consequences of actions and unknown values can be readily seen by all members of the drilling team. Specifically, a baseline of well pressure due to the mud density within the well (corrected for pressure and temperature) is established and (estimated or measured) pore pressures and fracture gradients depicted relative to this baseline in pressure units.

2. A means whereby potential operational decisions and the impact of these decisions can be accurately, comprehensively and quickly assessed by members of the drilling team prior to such decisions being made, such that un-necessary risks can be avoided and such that mitigations to issues that arise during the drilling operation can be properly evaluated.

3. A means whereby the impact and operation of a Managed Pressure Drilling (MPD) system can be readily visualized and controlled.

4. A means whereby well pressures (relative to the static pressure caused by the mud density) can be plotted on the x-axis with either True Vertical Depth or Actual Measured Depth plotted on the y-axis. The ability to use Actual Measured Depth enables this approach to be very effective/applicable to horizontal or high angle wells. For horizontal wells, the plot may be rotated such that the user is far better visually connected to the orientation of the well.

5. A means whereby (in real time) any well exposure to an underbalanced occurrence can be combined with knowledge of the well formations (for example, from LWD) and as a result be assessed and quantified, such that appropriate action can be taken.

6. The application of this approach to all wells, not just wells such as those shown in the examples. This new analysis/visualization will work for all well geometries and operating conditions. The examples chosen are just examples to clarify the merits of the approach. The examples are shown using “oilfield units” (that is feet and psi). The same approach can be used for other unit systems such as the metric system.

7. A means of updating the conventional/traditional approach to this issue (which has been used for many years—approaching 100 years), to account for the combination of the difficulties encountered in drilling wells which are far more challenging today and the availability of a vast array of new technology and information that is now available during the drilling of a well.

* * * * *