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IN-SITU STRESS AND STRESS REGIMES IN RELATION TO DRILLING OIL AND GAS WELLS

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ABSTRACT

In-situ stresses play the most important role on the borehole stability during drilling operations. Oil and gas companies are drilling progressively deeper wells, reaching out to more complex geological environments, and complex well trajectories. With the advent of commercially producible shale gas, more drilling and fracturing activities are being conducted in shale zones. Shale formations have quite different mechanical properties then conventional reservoir rocks such as sand stone or lime stone. Consequently, problems such as wellbore instability, fracture, collapse, wash out, etc., are increasing remarkably. These are undesirable and very costly incidents for the companies. Therefore it is imperative to conduct more research in this area to gain better insight to the failure mechanism and plan for safer drilling. A significant amount of research has been done and published over the last decade regarding this area. This paper presents a review of the different methods and models to determine in-situ stresses.

Keywords: Drilling, Borehole Stability, In-Situ Stress

1. INTRODUCTION

In situ Stress means the rock stress acting at the undisturbed region in the underground. Normally in the tectonically relaxed basin, three in-situ stresses are encountered: (i) vertical or overburden stress (σ_v), (ii) maximum horizontal stress (σ_H), and (iii) minimum horizontal stress (σ_h). Knowledge of the virgin stress field is very important in many problems dealing with rocks and other sub surface formations in Civil, Mining and Petroleum engineering. Vertical stresses are relatively easy to determine, but horizontal stresses are much more difficult to establish. Figure 1 shows the contributions of different researchers to the subject.

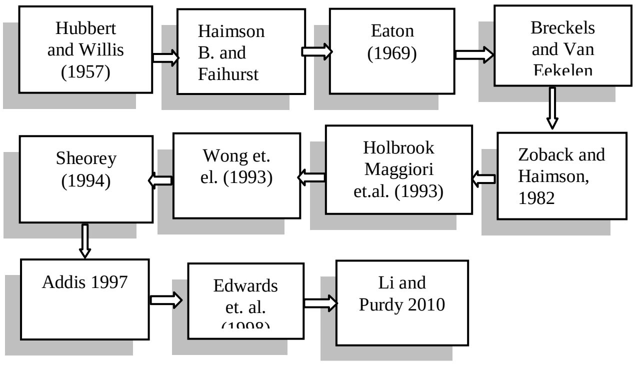

Fig.1 In-situ stress estimation by different

In a homogeneous, isotropic formation the principal stress components are simple to describe. Presence of faults change the axes and magnitudes of the stresses as shown in Figure 2. Different types of faults are (i) Normal (NF), (ii) Reverse (RF), and (iii) strike-slip (SS) [5]. ψ is the angle between the maximum principal stress and the failure plane..

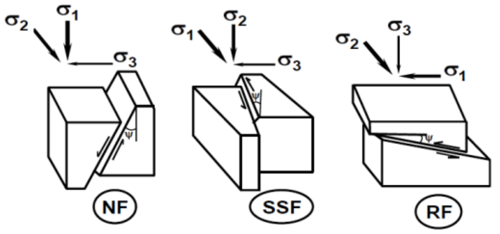

Fig 2. Stress axes and faults for relative stress magnitudes

2. ESTIMATION OF IN-SITU STRESS

For a basin that is not tectonically active, the two horizontal stresses, σ_H and σ_h can be assumed to be equal in magnitude. In a passive basin, σ_v is higher than the horizontal stresses. The following empirical expression (eq. (1)) was developed for the magnitude of the least principal stress as a function of depth in the Gulf of Mexico region [1,3]

$$\sigma_{hmin}=0.3(\sigma_V-P_p)+P_p \qquad (1)$$

Where, the constant 0.3 was empirically determined from the analysis of hydraulic fracturing data. A similar relation for the fracture pressure was proposed by equation (2) [5]

$$\sigma_{hmin}= K_i(\sigma_V-Pp\ )+P_p \qquad (2)$$

Where K_i is a function of z and normally found the value 0-2 [4,5]. Using this relation, functions for the Louisiana Gulf coast and South Texas Gulf coast region were proposed that varied in a non-linear fashion from 0.4 and 0.48 at 2000ft to values exceeding 0.7 at depths greater than 10,000ft [5]. The following correlation was developed for the least horizontal stress [4].

$$\sigma_H = \sigma_h = \left(\frac{\mu}{1-\mu}\right)\sigma_V + P_p\left(\frac{1-2\mu}{1-P}\right) \qquad (3)$$

Another set of correlations were developed for different regions to estimate the minimum horizontal stress, using instantaneous shut in Pressure (ISIP). These are shown in Table 1 [5].

Table 1: Minimum Horizontal stress and Stress Depletion rate correlations in worldwide Basin

Region	Depth Range (ft)	σ_h (psi)	Stress Deplation ratio
US Gulf Coast	0 to 11,500	$0.197D^{1.145}+0.46\ (P_c-P_{cn})$	0.46
	>11,500	$1.167-4596+0.46\ (P_c-P_{cn})$	0.46
Venezuela	5,900 to 9,200	$0.21D^{1.145}+0.56\ (P_c-P_{cn})$	0.56
Brunei	0 to 10,000	$0.21D^{1.145}+0.56\ (P_c-P_{cn})$	0.49

From Leak off test data of the North Sea basin, the ratio of Minimum horizontal stress to vertical stress were determined [5] as shown in Table 2.

Table 2: Trend of σ_h/σ_v with Depth in the North Sea

Region	σ_h/σ_v
Northern North Sea	$10^{-5}D + 0.7515$
Central North sea	$2x10^{-5}D + 0.7439$
Southern North sea	$3x10^{-6}D + 0.8854$

The most reliable way of determining the minimum in-situ total stress (σ_h) is by a mini-frac or micro-frac test. Although less précised, σ_h can also be estimated indirectly from leak-off tests (LOTs). The leak-off point (LOP) in a LOT generally corresponds to the mud pressure at which the formation starts taking in mud fluid. Data from 470 LOTs in the central Graven, North Sea was used to develop correlations for $\sigma_{h,}$ and σ_v with respect to depth, as shown in Table 3 [2, 5].

Table 3: In-situ stress and Pore Pressure Correlations for Central Graven North Sea

Parameter	Correlations
Minimum Horizontal stress	$\sigma_h= 31.5+0.472 x D +3.228 x 10^{-5}x D^2$
Vertical (Overburden stress)	$\sigma_v= 49 +0.747 x D +1.44 x 10^{-5}x D^2$
Pore Pressure	$P_p= (\sigma_h-0.55\ \sigma_v) / 0.45$

A porosity based technique for estimation of the least principal stress based on force balance concept was developed [3] as in equation (4)

$$\sigma_{h\ min} = (1-\varphi)(\sigma_V - P_p) \qquad (4)$$

As porosity of over pressured shale is typically ~35%, it yields similar values to that predicted with Ki~65%. From analysis of paper (Equation (2)) we said that the over pressure zone of any depth of shale would seriously overestimated the least principal stress. The following methods were proposed [3] to calculate the upper bound σ_H based on generalized Hook law with the equilibrium of stresses and pore pressure:

$$\sigma_H^{max} = \frac{(\sigma_h - \alpha_\beta P_p)}{\vartheta} - \sigma_v + 2\alpha_\beta P_p \qquad (5)$$

An improved method to determine σ_H using observations of breakout width [4] when the rock uni-axial compressive stress is known and is given by Equation (6):

$$\sigma_H \le \frac{\sigma_{ucs}+(K+1)P_{mud}-\alpha_\beta(K-1)P_p-(1-2Cos2\beta_b)\sigma_h+\sigma^{\Delta t}}{1+2Cos2\beta_b} \qquad (6)$$

Where is $2\beta_b$ the wellbore breakout angle, P_{mud} is the mud pressure, $K = (1+Sin\phi_f)/(1-Sin\phi_f)$, ϕ_f is the angle of internal friction and $\sigma^{\Delta t}$ is the thermal effects stress. It has been suggested that Normal faulting Horizontal stresses are typically smaller between 25 and 50% than of the vertical stress. In the regions with folding or thrust faulting, the Horizontal stress is typically between 200 and 300% higher than vertical stress. Further more local structures can considerably alter the regional in-situ stress [5].

3. MODEL RELATED TO IN-SITU STRESS MEAUSUMENT

Two simple models for σ_h are presented next. Both models are applicable where gravitational loading is the dominant (or only) source of stress. In more complex settings (where tectonics play important role), a more sophisticated model may be required or more reliance empirical calibration may be needed.

3.1 Uni-axial Strain Model (USM)

The magnitude of horizontal stress is determined by the elastic properties of the rock, especially Poisson's ratio. A rock with low Poisson's ratio, when loaded vertically and constrained on both sides, will transfer only a small amount of the load sideways to generate horizontal stress. A material with high Poisson's ratio will transfer more load, generating a higher horizontal stress. A material with Poisson's ratio equal to 0.5 will transfer the entire load sideways such that the vertical and horizontal stresses are equal [1]. If it is assumed that not only is there no horizontal strain but that the sediment behavior is also linear, isotropic, and elastic, the magnitude of both horizontal stresses can be expressed simply as a function of the vertical stresses, pore pressure and Poisson's ratio. In reality, these assumptions probably don't hold over geologic time. Compacting and diagenetic processes that occur as rocks are buried and are subjected to pressure and temperature detract from assumption of linear isotropic elasticity. The USM is therefore more suitable for describing relatively small changes in horizontal stress that occur over short periods of time such as during reservoir depletion. The most convenient way of considering the USM is in terms of effective stress. The effective stress is defined as stress deducted from pore pressure. Here it is assumed Biot's constant α_β=1, such that effective vertical stress (σ'_v) is given by:

$$\sigma'_V = \sigma_V - P_p \tag{7}$$

And horizontal effective stress (σ'_h) is the total horizontal stress minus pore pressure:

$$\sigma'_h = \sigma_h - P_p \tag{8}$$

The USM can then be expressed in terms of the ratio of the effective pressure and Poisson's ratio (ν):

$$\frac{\sigma'_h}{\sigma'_V} = \frac{\vartheta}{1-\vartheta} \tag{9}$$

Alternatively, the total horizontal stress can be expressed as

$$\sigma_h = \left(\frac{\vartheta}{1-\vartheta}\right)\sigma'_V + P_p \tag{10}$$

As shown in the above equation ν of the rock that controls the magnitude of σ_h for a given σ_v and pore pressure (P_p). Poisson's ratio can be determined experimentally in the laboratory on core samples. Poisson's ratio can also be determined, where both compression and shear wave velocity measurement are available from:

$$\vartheta = \left(\frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{2\left(\frac{V_p}{V_s}\right)^2 - 2}\right) \tag{11}$$

The Poisson's ratio of equation (11) is called the dynamic Poisson's ratio because it is derived from high frequency (dynamic) deformations. Under in-situ loading conditions, it is the static ν (that is obtained in laboratory measurements over a period of minutes to hours) that is more applicable to geological conditions. Thus, some conversion from dynamic to static ν should be applied in order to use these log-based ν values in the USM. Dynamic ν used with the USM may still give a sense of the contrast in σ_h between different lithologies. For example, adjacent lithologies with very similar dynamic ν might be expected to have a similar value of σ_h, where as stress contrast might be expected between adjacent lithologies with significantly different dynamic ν.

In Practice σ_h derived from the USM needs to be corrected to the absolute magnitude of σ_h as obtained from some kind of measurement or test. The widely used Eaton fracture gradient equation is an example of this type of correction (in which fracture gradient and σ_h are assumed to be equivalent). Eaton's fracture gradient is purely empirical and are based on results of LOTs. The standard leak of Pressure (LOP) however is often used as an approximation to σ_h. LOT are almost always performed in Shale [1].

3.2 Frictional Equilibrium Model (FEQM)

The FEQM [1] describes the state of stress in settings, it could be applied to determine the magnitude of the σ_h in any active faulting environment provided the magnitude of the σ_H is known. However, it is most easily applied in normal faulting environments (where gravitational loading is the only significant source of stress). It is also worth noting that in any active faulting environment, even when absolute stress magnitudes are not known, The FEQM can provide a useful method of constraining the ratio of the maximum and minimum stress if the frictional strength of the rock is known [1,2]

There are a number of criteria for describing rock failure that could be used in the FEQM. One of the most commonly used is the M-C criterion, which is based on frictional sliding of two surfaces. This can be used to obtain the magnitude of the minimum effective stress (In the simple gravitational loading model, this is the horizontal stress in the plane perpendicular to the fault plane) as a function of the maximum (vertical) effective stress and the shear strength of the sediment. If it is assumed that the existing faults have formed at the appropriate angle (i.e., it is on these planes that the failure condition is met) and that there is no cohesion on these faults, then the magnitude of the minimum total stress is expressed as:

$$\sigma_h = \left[\frac{1 - \sin \phi}{1 + \sin \phi}\right] \sigma'_v + P_p \qquad (12)$$

The friction angle (φ) in this case is that of the material in the existing fault zones. Because this parameter refers to post failure properties, it is sometime called the residual friction angle, which is typically lower than the internal friction angle of intact rock. Values of $\varphi_{residual}$ can be measured in the laboratory. Values between 11 and 20^0 have been reported [1] for weak Shale. Higher values would be expected in more sandy material and stronger rocks. Although variation in σ_h calculated by both the USM and the FEQM for assumed values of Poisson's ratio and $\varphi_{residual}$ respectively under two different pore pressure regimes are constants with depth, in reality, these values usually appear to change with depth.

Hubbert and Willis [1] are generally credited with the first attempt, The FEQM, the USM and all subsequent attempts to describe the variation of Fracture Pressure (FP) / or σ_h with pore pressure and vertical stress have followed the same basic format, using an equation of the form:

$$FP = K(\sigma_v - P_p) + P_p \qquad (13)$$

K is typically referred to as either the matrix stress coefficient or the effective stress ratio. If FP is assumed to interchangeable with σ_h above equation can be rearranged for K to show that it is equal to the ratio of the horizontal to the vertical effective stress – hence the name effective stress ratio:

$$K = \left[\frac{\sigma_h - P_p}{\sigma_V - P_p}\right] \qquad (14)$$

In the USM, K is a function of an elastic parameter, The Poison's ratio ν of the rock:

$$K = \frac{\vartheta}{1 - \vartheta} \qquad (15)$$

And The FEQM, K is a function of a strength parameter, the internal friction angle φ of the rock or of the Fault material

$$K = \left[\frac{1 - \sin \varphi}{1 + \sin \varphi}\right] \qquad (16)$$

It should be remembered that these models are very much simplifications of reality and the assumptions such as Isotropic linear elasticity and uni-axial strain are rarely satisfied[1].

4. RELATIONSHIP BETWEEN LOP's AND σ_h

The LOP (leak off pressure) is used routinely as an estimate of σ_h. The LOT (leak off test), however, is not performed to measure σ_h and can therefore sometimes yield misleading result. The LOT typically is performed after drilling out the casing shoe in order to determine whether the cement job successfully isolated the casing annulus and to estimate the upper safe limit for MW or equivalent circulating density to drill the next hole section. XLOT (extended LOT) is a procedure very similar to that of a hydraulic fracturing stress measurement performed specifically to measure σ_h in scientific borehole [2] , or a mini-frac performed to determine various parameters (including σ_h) required for the design of a large reservoir fracture-stimulation job [1].

Figure 3 [1, 2] represents a pressure vs time record from an XLOT. Stage 1 is the initial pressurization once the well is shut in. The slope of the line is a function of the compressibility of the whole system (Fluid, Casing, Pumping lines and equipment, and the rock exposed to the test). LOP is usually defined as the point at which the pressure build up slope deviates from linearity. LOP represents the point at which the system stiffness decreases, which under normal circumstances is likely to be the initial opening of tensile fractures at the well bore wall.

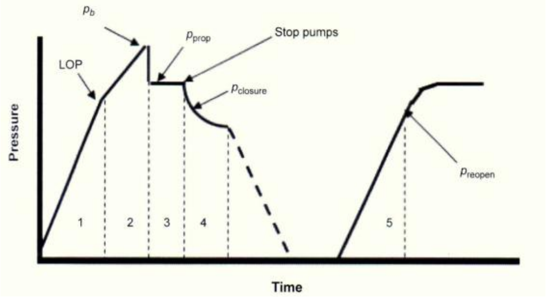

Fig 3. Pressure Vs time for an XLOT, The Standard LOT is typically stopped shortly after the LOP is seen

In the Standard LOT [1, 15] this initial deviation from linearity is where pumping is stopped. In the XLOT, pumping continues and the pressure is typically seen to continue to increase (Stage-2) until the breakdown Pressure (P_b) is reached. Breakdown is defined as the point at which the pressure actually drops, which indicates that the tensile fracture is growing at a faster rate than the rate at which the pumps are supplying fluid. After some volume of fluid has been pumped into the fracture to ensure that it has propagated some distance from the wellbore wall (at fracture-propagation pressure P_{prop}, stage-3), the pumps are stopped. During Stage 4, pressure bleeds off either to the formation if the system is closed or back to surface in a flow-back test, and the fracture closes. The pressure in the fracture just at the point where the fracture closes is called the fracture closer pressure ($P_{closure}$) and is a good measure of the stress acting perpendicular to the fracture. This is the minimum compressive stress (usually σ_h).

In an XLOT, a second pressurization cycle is then performed, which reopens the fracture (Stage-5). The fracture created Stage 1-4 is likely to remain hydraulically opens (albeit mechanically closed) after Stage-4. In this case, it will be pressurized along its length in the second cycle (Stage-5) such that the reopening Pressure (P_{reopen}) is again a good measure of σ_h.

Although $P_{closure}$ and P_{reopen} are the best quality measures of σ_h, they are rarely obtained because the XLOT is rarely performed. The Standard LOT, on the other hand, is performed at most casing shoes and therefore offers a much larger data set.

In the intact case Figure 4 (Case-1), the LOP will theoretically be equal to the breakdown pressure, which is a function of both horizontal stresses and tensile strength and can be significantly higher than σ_h , depending on the relative magnitudes of all these parameters. In this case, LOP may resemble a breakdown pressure in that it is followed by a distinct pressure drop.

In the case of pre existing cracks (Case-2), fluid can penetrate during pressurization to act on the sides of the crack and LOP is likely to be closure to σ_h. In this case, the LOT curve may be approximate the fracture re-opening part of the curve, and The LOP could be considered close to Pre-open, which as discussed is considered a good approximation to σ_h .

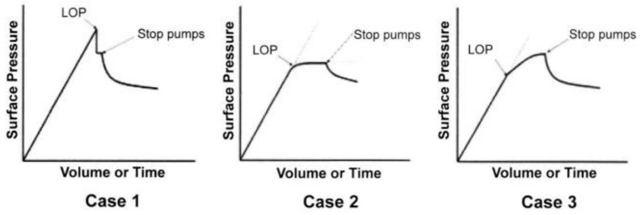

Fig 4. Various types of LOTs, representing different down-hole processes

The LOP from Case 1 may not be a good approximation to σ_h .The LOP from case-2 should be good approximation to σ_h and LOP from case-3 may be reasonable approximation to σ_h.[1].

At last the relationship between LOP and σ_h is a complex function of in-situ stress and the nature of pre-existing cracks as well as the properties of the fluid during the LOT. Care should be taken when using LOT data to estimate σ_h. It is recommended that the original pressure/volume record and any other operational information be reviewed in the interpretation of LOTs.

5. CONSTRAINING σ_H FROM FRICTIONAL EQUILIBRIUM

Borehole breakouts represent compressive-shear failure of borehole wall along the minimum horizontal direction where the maximum compressive hoop stress occurs. Generally, maximum horizontal stress must be determined from damage mechanics constraints based on borehole breakouts. In exploration wells, it is necessary first to drill a vertical pilot-hole. Wellbores fail in a manner which is strongly controlled by the magnitude and orientation of the in-situ stress field. The maximum horizontal stress can be estimated from the extended leak-off test (XLOT) with fracture reopening test [1,2]. This method was derived from the Kirsch solution for a circular hole subjected to an internal pressure in an isotropic, homogenous, and linear elastic medium. The assumption in the derivation was that the reopening occurs when the fluid pressure applied on the borehole wall is high enough to cancel the minimum tangential stress on the wellbore wall. Using elasticity theory and Mohr-Coulomb failure criterion for slippage on the fault [15] calculated the maximum horizontal stress for normal faulting and thrust faulting regimes. A proposed method for calculating the maximum horizontal stress when rock strength is known utilizing observations of breakout width from vertical wells and assumed when the maximum tangential stress on the wellbore wall is greater than rock uni-axial compressive strength (UCS), then the wellbore would fail.

The maximum horizontal stress magnitude σ_H is the most difficult parameter in the MEM (mechanical earth modeling) to determine. Unlike σ_h, which can be directly measured by the hydraulic fracture and LOTs, there are no methods to measure σ_H directly. For this reason, σ_H typically has to be constrained through model based approach. Two common approaches are frictional equilibrium on the observation of breakouts and DITFs, and third approach based on inversion of Leak off Data from multiple wells**.**

At a given value of σ_v, Pp, and σ_h, values, the upper limit of σ_H is determined by frictional strength of rock mass. The range of possible stress magnitudes for a given frictional strength can be illustrated as a stress polygon ref The stress polygon displays the permissible magnitudes of horizontal stress (assuming fictional equilibrium) for a given value of $\sigma_{v,\ Pp,}$ and $\varphi_{residual}$ there a three sectors to the polygon, each representing a different Andersonian faulting regime [20,21]. Figure 5,6 shown an example of two stress polygons. Figure 5 shows the permissible magnitudes of horizontal stress at a depth of 3km assuming hydrostatic pore pressure, a value of 30^0 for $\varphi_{residual}$ and known σ_v of 70 MPa [2]. Figure 6 shows the permissible magnitudes of horizontal stress for same assumption as in fig-5 except that is this case, Pp is significantly higher (this is an over pressured environment), the increased pore pressure has the effect of greatly reducing the range of possible stress values. This is consistent with the observation that in highly over pressured environments, we rarely see significant stress anisotropy. From both figure, the range of values of σ_H can be seen that are allowed for a known value of σ_h .

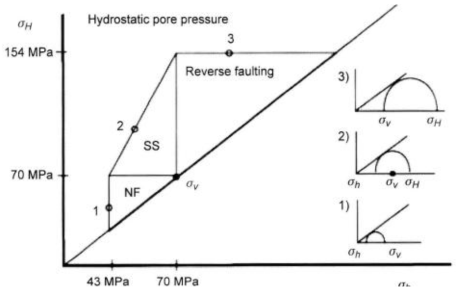

Fig 5. Stress Polygon (1-Normal faulting, 2- Strike/slip faulting, 3-Reverse faultinmg

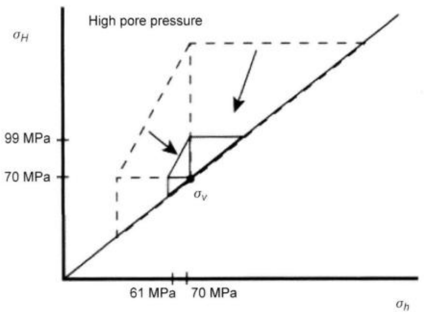

Fig 6. Effect of significant overpressure on the Stress of Polygon

6. CONSTRAING σ_H FROM OBSERVATIONS OF WELLBORE FAILURE

When stress concentration at the wellbore wall exceeds the rock strength, the rock in the wellbore wall will fail, either in compression or tension. When such a failure in a wellbore is observed and the wellbore pressure (MW) at the time of failure is known, the magnitude of $\boldsymbol{\sigma_H}$ can be estimated [1]. Different modes of stress-induced failure of the wellbore wall such as the most common are breakouts (Shear failure of the wellbore wall at relatively low MW) and DITFs, Drilling induced tensile fractures (tensile failure of the well bore wall at high MW). Where a breakout is observed in a wellbore that was exposed to a known MW, we can conclude, on the basis of the wellbore-stability calculation, that σ_H must be exceeded a certain value for the breakout to have formed. This places a lower limit on the magnitude of σ_H (i.e.. must be at least this high for the breakout to have formed).

On the other hand, in the case where no breakout is observed, we can conclude that magnitude of σ_H can't exceed a certain value; i.e., we can derive an upper limit (σ_H cannot be higher than this, otherwise a breakout would have formed).The observation of DITFs can also be used to constrain $\sigma_{H,}$ As for breakouts, the assumptions is that the wellbore pressure at which a DITF forms is a function of stress concentration (and therefore of $\sigma_{H,}$) at the wellbore wall (Kirch equation around a borehole). Under this assumption, high values of $\sigma_{H,}$ relative to σ_h tend to promote the formation of DITFs. Therefore, as the with the observation of breakout, Where a DITF is observed for a given wellbore pressure, we can calculate the lower limit of σ_H . In other words, we can say σ_H must be at least this high for a DITF to have formed. Although this method seems to be used quiet widely, there are a couple of points that should be keep in mind. First we apply kirsch equation to solve for $\sigma_{H,}$ we are assuming Boundary condition that behind kirsch equations are applicable. One of these Boundary conditions is that the wellbore wall is initially intact and impermeable. Estimates and measurements of tensile strength can vary quite widely, which adds some significantly uncertainty to the $\sigma_{H,}$ estimation.

When using observation of breakouts and DITFs to estimate $\sigma_{H,}$ it is important to know the pressure to which the wellbore has been exposed between being drilled and making the observation. However, Transient pressures such as swab and surge that occur during normal drilling practices must also be considered particularly for the case of DITFs. Ideally a time-based record of down-hole pressures should be used to ensure that the appropriate wellbore pressure is used in calculation.

7. INVERSION METHOD FOR IN-SITU STRESS DETERMINATION

It is a powerful method to compute the magnitudes and direction of the Principal in-situ stresses from multiple fracture (Leak off) data [9]. We normally take advantage of this directional uniqueness to back calculate the in-situ stress field from Leak off data. Assume that a number of production wells have been drilled in different directions. To illustrate this method, consider the equation for the fracturing pressure for a single bore hole:

$$P_{wf} = 3\sigma_y - \sigma_x - P_p \tag{17}$$

Where, σ_y and σ_x are the minimum and maximum stress components normal to the borehole direction. This two stresses are generally transformed from the vertical and two horizontal principal in situ stresses when considering deviated well boreholes.

The inversion technique [6,7,9] uses leak-off data to predict stresses in the formation, and also predicts fracturing pressures for new wells. The input parameters such as inclination, the fracture pressure, the pore pressure, overburden stress at each fracture location and the directional data which are the borehole azimuth and inclination are needed. Having two or more data sets, the inversion technique calculates the horizontal stress field that fits all data sets.

Assume fracturing process is governed by Eqn. 17, The two normal stresses are replaced by their transformation equations, by rearranging the result, Eqn. 17 now becomes:

$$\frac{P_{wf}+P_p}{\sigma_v} + \sin^2\gamma = (3\sin^2 a_z - \cos^2 a_z \cos^2\gamma)\frac{\sigma_k}{\sigma_v} + (3\cos^2 a_z - \sin^2 a_z \cos^2\gamma)\frac{\sigma_l}{\sigma_v}$$

Or in short form,

$$P' = a\frac{\sigma_k}{\sigma_v} + b\frac{\sigma_l}{\sigma_v} \tag{18}$$

The equation (18) has two unknowns, the horizontal in-situ stresses, called σ_k and σ_l. Having two data sets from two well sections with different orientation, one can determine these two unknown stresses. After calculating the stresses, the largest is redefined to σ_H and the smallest to σ_h . The inversion technique takes advantage of the process described above; often we have many data from many wells. These will be used in the following to calculate the two horizontal in-stresses and their directions. Assume that each data we have many data sets and in the matrix form the equation (18)

$$\begin{bmatrix} P_1' \\ P_2' \\ . \\ . \\ P_n' \end{bmatrix} = \begin{bmatrix} a_1 & b_1 \\ . & . \\ . & . \\ a_n & b_n \end{bmatrix} \begin{bmatrix} \sigma_k/\sigma_l \\ \sigma_l/\sigma_v \end{bmatrix},$$

In short form: $[P'] = [A][\sigma]$ (19)

Equation 19 is an over-determined system of equations since there are many sets of data available to determine the two unknown stresses. For these general cases there will always be an error between the solution and some of the data sets. The unknown stresses must also be isolated by determining the inverse of the equation above. To solve these issues, the error between the model and the measurement is:

$$[e] = [A][\sigma] - [P']$$

The square error is: $e^2 = [e]^T[e]$ (20)

The error is minimized by requiring: $\frac{\partial e^2}{\partial[\sigma]} = 0$

By performing the above analysis, the in-situ stress are given by

$$[\sigma] = \{[A]^T[A]\}^{-1}[A][P'] \quad (21)$$

At this stage we observe that the equation for the stresses Eqn. (21) is too cumbersome for manual calculations a computer program is required. Another issue not discussed so far is the determination of the direction of the in-situ stresses. Eqn.(21) is computed assuming a direction of the in-situ stresses from zero to ninety degrees. Simultaneously is Eqn. (20) is computed. The direction, at which the error is at a minimum value, is the direction of one of the horizontal in-situ stresses. Aadnøy et. al., 1994, gives a field case, demonstrating the application of the inversion technique to determine the in-situ stresses.

The maximum Horizontal stress is more difficult to estimate from single bore- hole measurements. Table2 [7, 9] Summarizes common methods used to assess the in-situ stress state. It is seen that the only method that simultaneously estimates both maximum and minimum horizontal stress and direction is the inversion method.

Table 2: Common methods to estimate the Principal In-situ stresses

Method	σH	σh	Direction of σh
Individual LOT	x		
Empirical LOT	x		
Extended LOT	x		
Inversion LOT	x	x	x
Breakout analysis			x

8. SUMMARY

The vertical stress or overburden (σ_v) at any point is a function of the density of all material above it. Maximum horizontal stress (σ_h) is estimated from a simple model correlation with effective vertical stress or empirically from estimates in offset wells based on LOTs, XLOTs, lost circulation, or hydraulic-fracturing tests. Similarly, while drilling the well, as pore pressure and vertical stress is updated, a model based $\sigma_{h,}$ should also be updated. Also if good LOT or lost circulation data are acquired while drilling, this should also be used to either confirm or update σ_h. Where vertical stress and/or pore pressure changes significantly from the predrilled estimate, so too will $\sigma_{h,}$. An unexpected pressure ramp or regression can have significant impact on $\sigma_{h,}$. Where significant components of subsurface stress are from sources other than gravitational loading (e.g., in tectonic settings, structurally complex settings and around salt), changes in $\sigma_{h,}$ may be related to factors other than pore pressure and vertical stress. In this more complex settings, update top $\sigma_{h,}$ are likely to require some direct measurement of $\sigma_{h,}$ (from XLOT for example). The magnitude $\sigma_{H,}$ is the most difficult parameter to determine. There is no direct way of measuring $\sigma_{H,}$ although this paper describes some of the ways to estimate $\sigma_{H,}$ through modeling, matched to observations of wellbore failure. This is also possible in the while drilling phase, using LWD images. In complex Tectonic environments, $\sigma_{H,}$ may be an important parameter that should be updated as the well is drilled. However, because of the difficulty of estimating this parameter, it appears to be rare that $\sigma_{H,}$ is updated while drilling. The most reliable method for stress estimation from an XLOT. Standard LOTs fracture the formation but do not have the required accuracy for stress measurement.

Minimum stress estimates can be obtained using a lower bound to the leak-off pressure data if there is sufficient quantity, or by potentially using the shut-in pressures from these tests if used with care as approximations to the minimum stress magnitude. The XLOTS and LOTS are predominantly performed in shale and mudstone formations which generally have the highest stress and fracture gradients. The stress data obtained from these tests should not be directly extrapolated to other Iithologies, e.g. sandstones where, in general, the fracture gradients will be significantly lower and especially so, if the pore pressures have been depleted through production. Regional stress maps will be helpful to designers and engineers to have the first estimate of the in-situ stresses.

Breakout is the zones that occur on the opposite side of the borehole due to spilling of the rock, especially when in-situ horizontal stress anisotropy exists in the region. However, in case of deviated wells the minimum stress direction cannot be estimated directly from the breakouts as its position changes in the borehole wall in relation to trajectory azimuth and to the in-situ stresses.. In some cases rock failure can happen due to orientation of the trajectory, drilling practices, improper mud property, and lower strength of the rock, to mention a few which are not directly related to the stress pattern of the area.

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