Strike-Slip
and Closure Stress

HALLIBURTON

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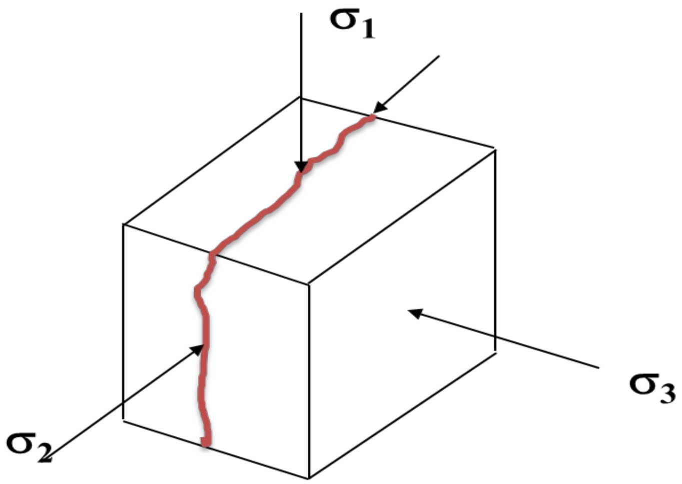
To discuss the issues around the concept of strike-slip stress regime, we first have to consider the in-situ earth stress tensor. In theory, the stresses acting on an element of rock in the sub-surface can be resolved into three orthogonal principal stresses. A principal stress is defined to be either pure compression or tension, with no shear component acting in the direction of the principal stress axis. In the diagram below, the three principal stresses are labeled 1-3, with σ_1 being the maximum compressive stress and σ_3 the minimum stress in the system. The principal stresses are generated through multiple processes including sedimentation, erosion, diagenesis, maturation, and tectonics. All three principal stresses change throughout geologic time.



In a "normal" stress environment, the vertical stress is the maximum. Vertical stress is caused by the weight of the overburden sediment and pore fluid and is related to the integrated bulk density from surface to the depth of interest. The total overburden weight is counteracted by the pore fluid pressure in the reservoir, at depth. Pore fluid pressure pushes upward against the overburden weight, and the projection of the fluid pressure is adjusted by Biot's poroelastic coefficient (alpha). The net downward stress causes the rock to deform under what is called "uniaxial strain". In this theory, the lateral deformation, or strain, is assumed to be zero because the rock element is contained in a rigid and infinite rock mass. While not perfectly true, this assumption is used as a starting point for theoretical stress estimates. Horizontal stresses are usually changed from the assumed uniaxial strain case by lateral movements in the earth crust (tectonics). The effect of tectonic strain can't really be computed from theory, so the stresses must be measured to understand the present-day state.

When conducting a hydraulic fracturing treatment, the induced hydraulic fracture must deform the surrounding rock to create an open fracture aperture. In this process, the amount of work done is always minimized. This means that the induced hydraulic fracture will always lie in the plane formed by the maximum and intermediate principal stresses and be perpendicular to the minimum stress in the tensor, regardless of the spatial orientation of the stress tensor. There will be no unresolved shear stresses on the exposed fracture surface. There will be shear stresses on any plane cutting through the block at any angle other than a principal stress axis. Hydraulic fracturing alters the pore pressure and induces strain in the rock, causing shear failure in the rock surrounding the hydraulic fracture (microseisms). Shear slip can alter the magnitude and direction of the principal stresses around the induced hydraulic fracture by relieving strain through slip along shear faces.

The measured “closure stress” in a fracture diagnostic test is the minimum stress in the tensor. The other two principal stresses cannot be directly measured. Fracture closure stress is usually reported as a “total” stress, which includes the net or effective intergranular stress supported by the rock framework (grains or solid fabric). The effect of pore pressure inside the rock also acts on the fracturing fluid and provides an additional component of stress. Since pore fluid pressure is isotropic, the orientation of the fracture is determined by the magnitude, direction, and difference of the three effective stresses, which take out the pore pressure component and refer to only the stress transmitted through the solid. For the remainder of this discussion, all references to stress indicate net effective stress and not total stress, unless otherwise explicitly noted.

As a reminder, the equation for the minimum total in-situ stress in the earth tensor (as applied in GOHFER) is shown below. The first term of the equation is the effective minimum horizontal stress generated through uniaxial strain. The last two terms account for tectonic stress and strain boundary conditions acting only on the minimum stress. During tectonic compression, prior to shear failure, the stress in the rock is proportional to the induced strain (ε) multiplied the static Young’s Modulus of elasticity (E). Once the shear failure limit is reached, a shear slip or fault plane forms and the elastic relationship between stress and strain is lost. After shear failure, a residual stress remains that is related to the frictional properties of the failed shear plane. The apparent fracture closure stress is the total minimum horizontal stress, or effective minimum horizontal principal stress plus pore pressure.

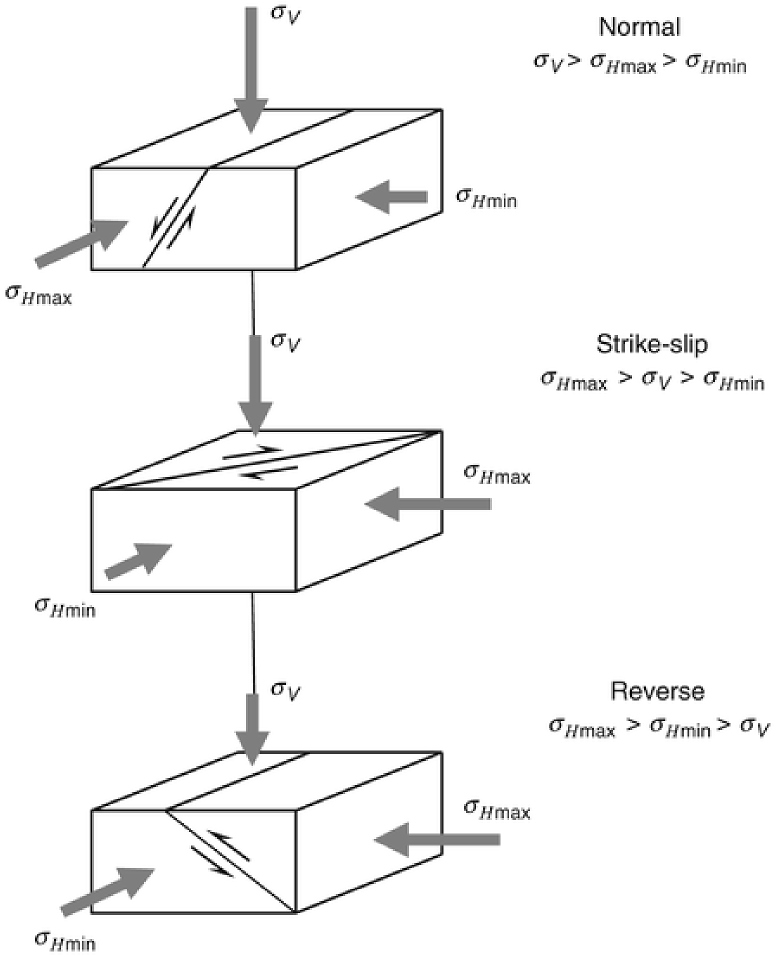
$$P_c = \frac{\nu}{(1-\nu)}\left[P_{ob} - \alpha_v P_p\right] + P_p + \varepsilon_x E + \sigma_t$$

- P_c = closure pressure, psi
- ν = Poisson’s Ratio
- P_{ob} = Overburden Pressure
- α_v = vertical Biot’s poroelastic constant
- P_p = Pore Pressure
- ε_x = regional horizontal strain, microstrains
- E = Young’s Modulus, million psi
- σ_t = regional horizontal tectonic stress

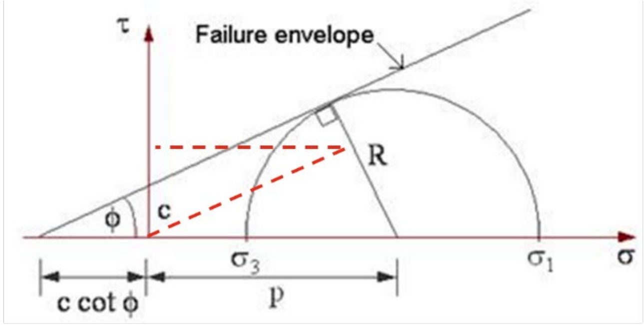
In a DFIT or any other determination of “closure stress” we can only measure Sh_min. Since the measured “closure stress” is a total stress, we also have to get an accurate measurement of pore pressure and know something of Biot’s poroelastic parameter (alpha) to get the minimum effective stress from closure stress. We generally get Sv from integration of a bulk density log, from surface to TD, or by an assumed regional overburden gradient (OBG). Sv (effective) is OBG * TVD – alpha*Pore_P. It is nearly impossible to directly measure SH_max, and this is where the problem creeps in.

We get reports that almost every reservoir, everywhere in the world, is in “strike-slip” stress conditions. A strike-slip fault is a near-vertical shear plane along which two rock segments slip laterally relative to each other. For this to occur the effective (intergranular) stress state must be such that:

SH_max > Sv > Sh_min



In a strike-slip stress regime it is usually assumed that the rock is at its shear-failure limit, based on a Mohr-Coulomb failure analysis, illustrated below. In the diagram, for strike-slip conditions, σ_1 must be SH_max and σ_3 is Sh_min. The effective vertical stress falls between them. The angle of the failure line, with respect to the normal stress axis, is the internal angle of friction and is usually taken as an "average" of about 30 degrees. Data on real rocks, from the CoreLab Tight-gas and Shale consortia, show that the friction angle can actually vary from about 10-degrees to 60-degrees, so the "average" is often not very useful. The intercept of the failure line with the shear-stress (vertical) axis is called the rock cohesion. This is very difficult to measure in a lab except by interpretation of multi-point Mohr-Coulomb failure tests. It is nearly impossible to measure in-situ. It is often assumed that there will be weak planes, or cohesionless surfaces in the rock which would account for the weakest shear failure, indicated by the red dashed line. The orientation of these weak planes, relative to the stress tensor, is practically never known.



- Shear failure is defined by “cohesion”, c, and “friction angle”, ϕ
  - Assume c=0 and ϕ=30 degrees, R=2ϕ
- Use net overburden (TVD-Pp) and net closure (Pc-Pp) as max and min stresses
- Maximum strain is approximately $\{0.2*(\sigma_1+\sigma_3)\}/E$

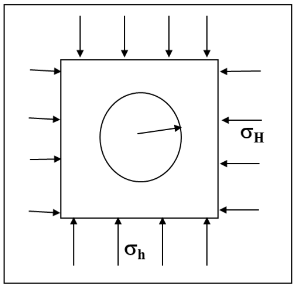
For completeness, the intercept of the failure line (assuming positive cohesion) at the negative point on the effective stress (horizontal) axis, represents the theoretical tensile strength of the material. A Mohr’s circle tangent to the failure line and with its minimum effective stress anchored at zero, defines the unconfined compressive strength (UCS) of the material by the maximum value of the circle’s intercept with the effective stress axis.

For a perfectly vertical, intact borehole (no pre-existing fractures) in an isotropic and homogeneous formation, the stresses around the hole can be computed using the Kirsch equations (1898).

$$\sigma_r = \frac{\sigma_h + \sigma_H}{2}\left(1 - \frac{r_w^2}{r^2}\right) + \frac{\sigma_h - \sigma_H}{2}\left(1 - 4\frac{r_w^2}{r^2} + 3\frac{r_w^4}{r^4}\right)\cos 2\theta + \frac{r_w^2}{r^2}(P_w - \alpha P_o)$$

$$\sigma_t = \frac{\sigma_h + \sigma_H}{2}\left(1 + \frac{r_w^2}{r^2}\right) - \frac{\sigma_h - \sigma_H}{2}\left(1 + 3\frac{r_w^4}{r^4}\right)\cos 2\theta - \frac{r_w^2}{r^2}(P_w - \alpha P_o)$$

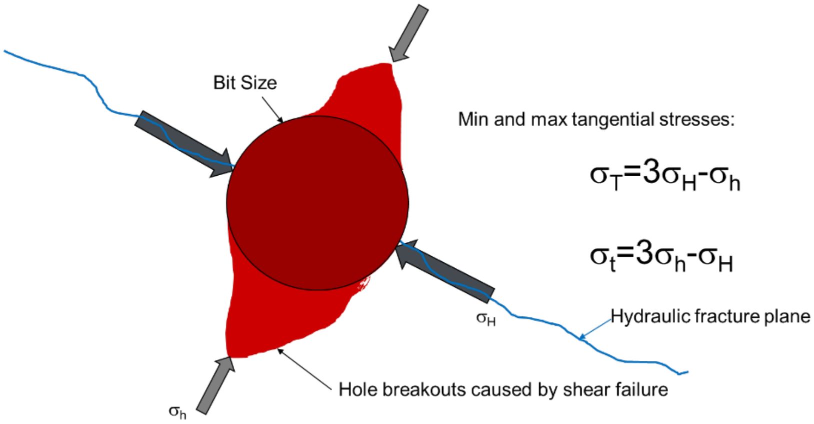
$$\sigma_v = P_{ob} - \alpha P_o$$



P_o = far field pore pressure
P_w = wellbore fluid pressure
P_{ob} = overburden pressure
r = distance from wellbore
σ_H = maximum horizontal stress
σ_h = minimum horizontal stress
θ = angle from direction of minimum stress

For this special condition it is theoretically possible to measure the (open hole) breakdown pressure and closure stress (Sh_min). The breakdown pressure represents (ideally) the minimum tangential net stress, T_net or σ_t in the diagram below, around the circumference of the hole, plus pore pressure. The difference between observed breakdown pressure and pore pressure (neglecting Biot's alpha for horizontal stresses) is the minimum net tangential stress on the borehole. The relation of this net tangential stress (T_net) to the far-field principal stresses is:

T_net = 3 * Sh_min – SH_max



This approximation ignores PZS or rock tensile strength, so is much less useful in the real world, but can help set limits on the assumed value of SH_max. If, after breakdown, the pressure decline is observed and analyzed (by DFIT), then the net closure stress (total closure stress minus pore pressure) can be determined. This gives Sh_min. Knowing T_net and Sh_min, the magnitude of SH_max can be determined:

SH_max = 3 * SH_min – T_net

Using the data from the "Vertical Tight Gas" training example, and assuming a BH breakdown pressure of 10,600 psi (guessed, because in the actual case there was no breakdown), we can get a guess at the in-situ stress tensor. Depth is 11370', pore pressure is 6035 psi, and total closure stress is 8735 psi, with Biot's alpha=0.817. This gives Sv_net = 6440 psi. Sh_min = 2700 psi, and T_net = 4565. This implies that SH_max = 3535 psi and gives a horizontal net stress anisotropy of 835 psi. In GOHFER, the input stress anisotropy is applied to the total minimum stress (8735 psi), so the effective anisotropy is 0.0956. This is a "normal" stress environment.

The assertion that almost all reservoirs are in strike-slip stress comes, invariably, from analysis of safe mud weight for drilling. Because of the high tangential stresses around a borehole, especially when drilling at an inclination between 30 and 60 degrees, and normal to SH_max, the drilling mud weight must be high enough to prevent shear or collapse failure of the borehole. Getting an accurate determination of the collapse mud-weight requires exact information about the rock mechanical properties of each layer drilled through (effectively by the foot), along with the pore pressure and magnitude and orientation of the entire three-dimensional stress tensor. Since the actual rock strength or borehole failure conditions are affected by local natural fractures, bed dip, chemical interaction with the mud, time-dependent rock creep, mechanical wear of the drill string, and other factors, these "safe mud-weight" estimates are usually intended to be conservative.

With no direct measurement of in-situ rock strength under the actual conditions of drilling, and no practical way to directly measure SH_max, the common assumption made in drilling software is that all rocks are in their worst-case stress state, which is at their shear-failure limit. So, by definition, all rocks are assumed to be in a "strike-slip" stress environment in this analysis. It's interesting to note, from a historical perspective, that Nolte used to advocate the same thing: If you can't measure SH_max, assume that all rocks in the earth are stressed to their shear failure limit. In the Mohr-Coulomb diagram shown above, this is the method we employ to get the maximum allowable tectonic strain offset that can be applied in calibrating a model. If σ_3 is the net closure stress, and σ_1 is the net overburden stress, then the maximum compressive strain that can be applied, without causing shear failure, through reverse faulting, is approximately $(\sigma_1 + \sigma_3)/(5^*E)$, where E is static Young's Modulus in million-psi. This approximation is for large-scale rock failure and assumes that cohesionless planes exist somewhere in the system.

For the Vertical Tight Gas case, and modulus of about 5e6 psi, this is a maximum strain of 457 microstrains. This imposed strain would generate a net stress differential of 2285 psi at failure. This is a useful check when someone gives an estimated SH_max value for a supposed strike-slip reservoir. If the maximum net stress given for your reservoir exceeds this limit, there may be something wrong. I have also seen many cases where the assumed strike-slip SH_max would predict a negative breakdown pressure, for a perfectly vertical well. This is also something that should be cross-checked.

For an extensional tectonic system, the same approximation can be applied to determine the conditions for tensile failure, or normal faulting, when the Mohr's Circle shifts left and contacts the failure line. For the same example with minimum net stress of 2700 psi, using (2700+0)/(5*E), the allowable negative (extensional) strain is -108 microstrains. These relations provide useful estimates but are not exact and do not account for rock fabric effects.

Assuming all rocks are at their shear failure limit is OK, and "safe" for drilling conditions because it will always provide the minimum safe mud weight window between collapse and tensile failure for drilling. In Nolte's world of single vertical fractures on vertical wells, the assumption is also acceptable. When dealing with horizontal wells, which may be drilled at any azimuth relative to the stress tensor, the assumption is not acceptable. Assuming all reservoirs are "strike-slip" can easily bring up conditions that are impossible to treat through hydraulic fracturing or lead to unrealistic fracture geometry results.

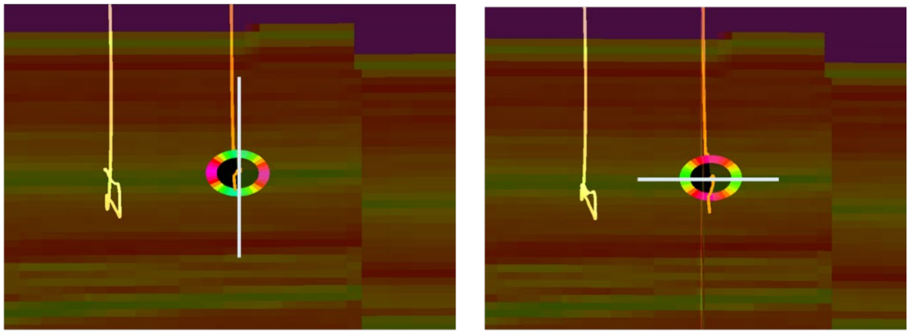
One other consideration: If rocks have ever been subjected to sufficient tectonic strain to reach their failure limit, they will break, and faults will activate. This is the cause of earthquakes! When a fault slips some, or all, of the strain energy will be dissipated or released. So, if a rock reaches its shear-failure limit, a fault slips and the differential stress in the system that caused the faulting is relieved. Continued tectonic movement can build up additional stress, until the fault slips again. These are the conditions, most famously, along the San Andreas fault in California which is a strike-slip fault. If we happen to be stimulating wells in a tectonic thrust or shear environment that has mapped strike-slip or thrust faults, it is impossible to know what the current stress state is, or how much strain energy or stress anisotropy exists in the current state and how much has been dissipated from fault slip.

One other pet peeve on this subject: Injecting water into a fault does not “lubricate” the fault and cause it to slip. The rocks around the fault are already saturated with fluid, usually water. Injection into a fault causes a local increase in pore pressure. The increased pore pressure reduces the effective stress (force) acting normal to the fault plane and allows it to slip. Remember, the force needed to overcome sliding friction is the normal force times coefficient of friction. It is unlikely that water injection will change the coefficient of friction along the already water-saturated fault face but will definitely change the normal force. If a reservoir stress state is in strike-slip conditions, at its incipient shear failure point, then any injection above fracture pressure should cause a macro-seismic event, or earthquake. If we don’t cause earthquakes every time we pump into a well, we are probably not commonly dealing with strike-slip stress conditions.

In summary, practically every time a “geomechanics” consultant gives you a stress tensor estimate, they will tell you that you are in a strike-slip regime. Mostly, they think they are giving you the “safest” bet but it is not usually correct. In my experience, almost every reservoir in the world has been described as “strike-slip” and very few actually are, even in tectonically active areas. Look at the data you have to constrain the stress tensor as accurately as possible. Do a DFIT correctly and pay attention to the apparent fissure-opening pressure. If you see secondary fracture activation (fissure opening), you know the stress anisotropy is larger than the difference between the fissure opening pressure and closure stress, which is what we define (in GOHFER) as CFOP. Since we don’t know the azimuth and orientation of the activated secondary fissures, we can’t really get the total anisotropy. If the fissures are vertical and perpendicular to the main fracture, then CFOP equals horizontal stress anisotropy. If the angle between the fissure plane(s) and dominant hydraulic fracture is less than 90-degrees, the horizontal stress anisotropy will be more than CFOP.

One last thing to check, for horizontal and inclined wells: Get the well azimuth right in the well construction and grid setup. Look at the “Breakdown Pressure” 3D display in the GOHFER Grid Setup and see what the minimum and maximum breakdown pressures are for the well, when using your assumed input maximum horizontal stress, CFOP, or input stress anisotropy. If the minimum tangential stress, or breakdown orientation is horizontal you are in trouble. If the input data are correct, you will only get a horizontal “pancake” fracture and treating pressures will greatly exceed overburden stress. If the predicted breakdown pressures are completely out of whack compared to the observed breakdown or treating pressures in the field, even for vertical fracture orientation, your assumed stress anisotropy should be carefully reconsidered.

Induced fracture orientation shown by blue line.

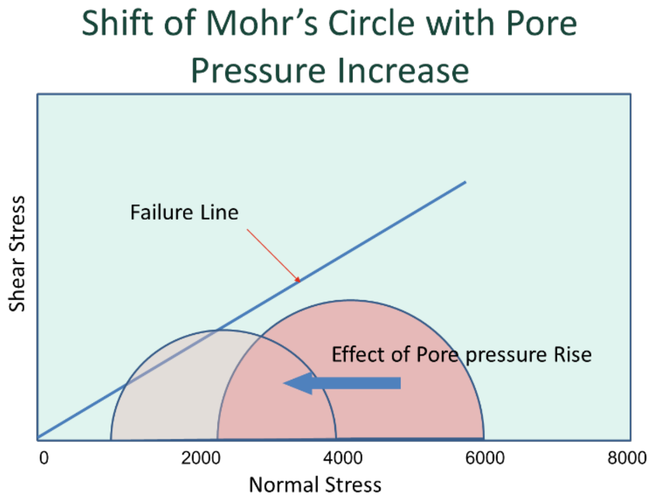


Normal Stress Breakdown:
Anisotropy based on CFOP (~830 psi)

Strike-Slip Stress Breakdown:
40% Stress Anisotropy (~2240 psi)

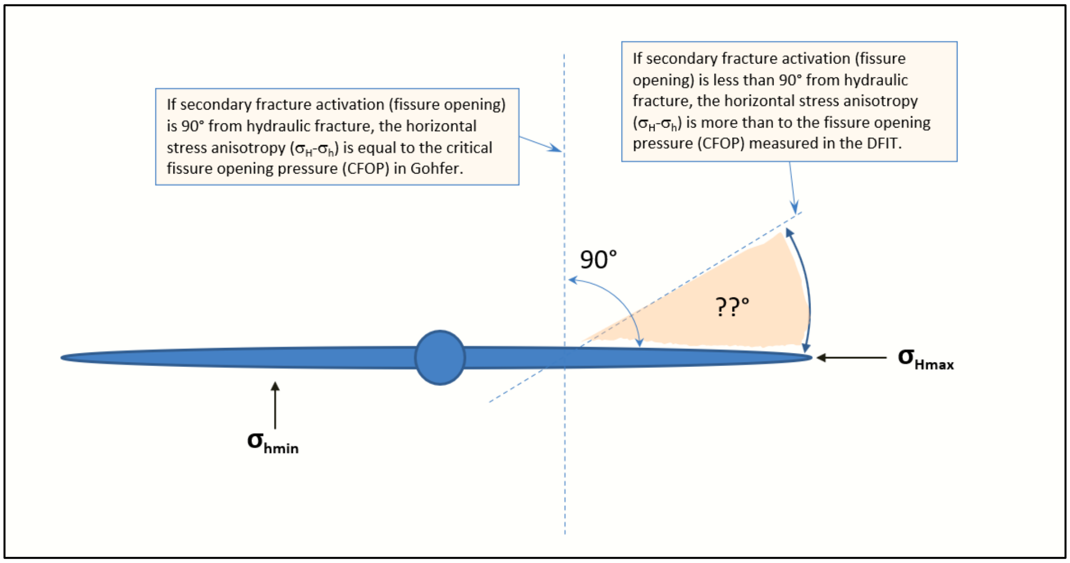
One might think that the maximum horizontal effective stress might exceed the effective vertical stress, if the pore pressure were abnormally high. High pore pressure “lifts” the overburden and decreases the effective stress. The problem with this is that a low effective vertical stress reduces the horizontal stresses generated through gravitational loading. Low minimum horizontal stress means that the internal friction in the rock mass is so low that it can’t support any significant differential stress. In the Mohr-Coulomb diagram, the Mohr’s circle minimum will be nearer zero stress. The relatively small difference between the minimum and maximum allowable stresses at shear failure will likely result in spontaneous shear, probably as the pore pressure rises (due to hydrocarbon maturation). The ultimate result is that the horizontal stress anisotropy we are likely to encounter is very small because the rock is not strong enough in shear to support much anisotropy. Evidence that shear has occurred is often seen as slickensides in vertical cores. These are striations in rock strata caused by slippage along weak planes that causes gouging of the slippage surface. Slickensides are common in the over-pressured deep Eagle Ford.

The only case where problems are likely to occur is when both horizontal stresses are controlled by tectonics, not gravity, and the vertical effective stress is minimum. This is a reverse or thrust fault regime, not strike-slip. In this case, practically all induced hydraulic fractures will be horizontal or bedding parallel. This is discussed in detail in SPE 134142 (2010).



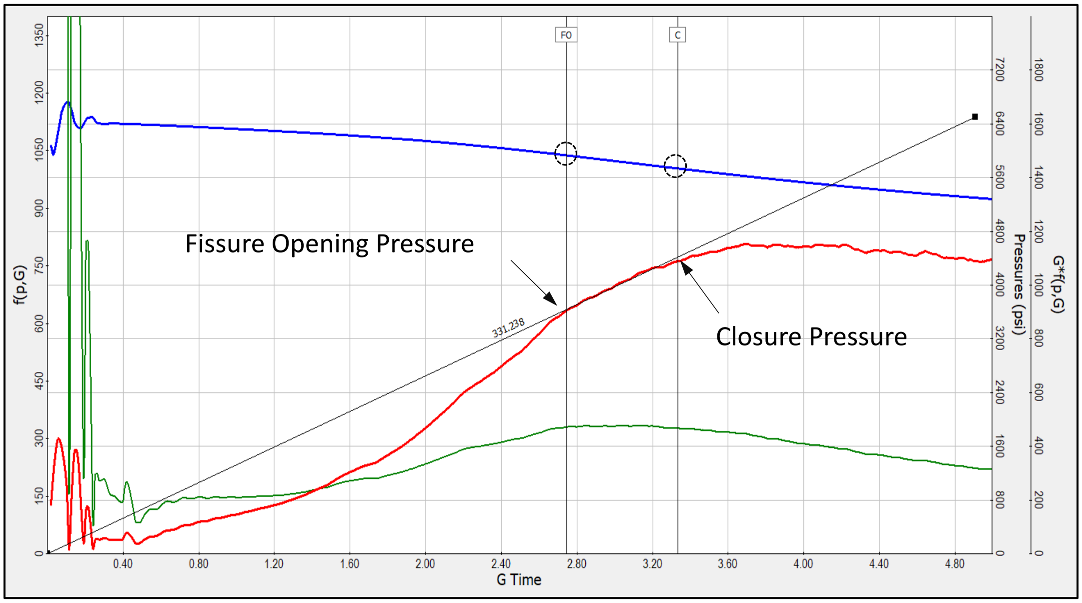
Appendix:

Check Fissure Opening Pressure in DFIT:

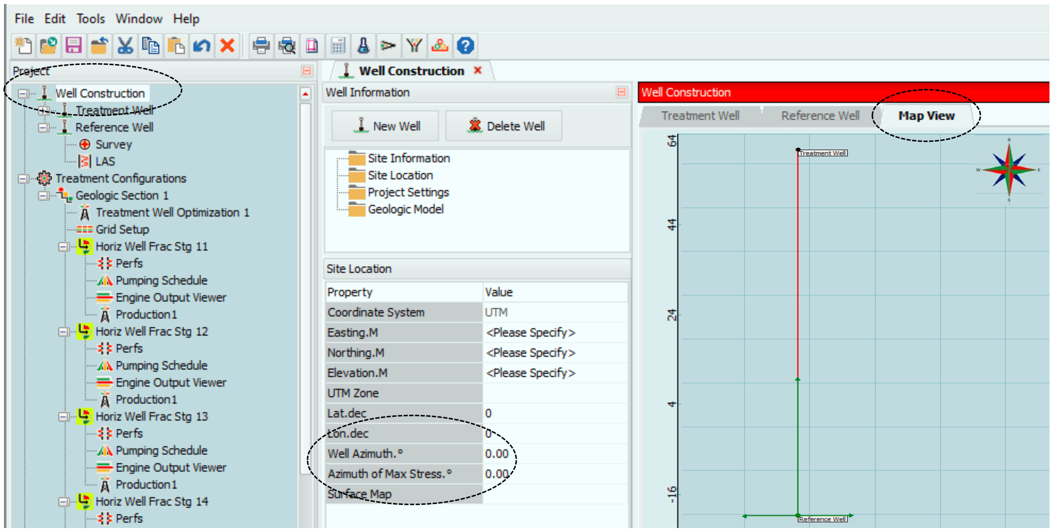

If secondary fracture activation (fissure opening) is 90° from hydraulic fracture, the horizontal stress anisotropy (σ_H-σ_h) is equal to the critical fissure opening pressure (CFOP) in Gohfer.

If secondary fracture activation (fissure opening) is less than 90° from hydraulic fracture, the horizontal stress anisotropy (σ_H-σ_h) is more than to the fissure opening pressure (CFOP) measured in the DFIT.

Example of Fissure Opening Pressure in DFIT with Variable Storage Signature:

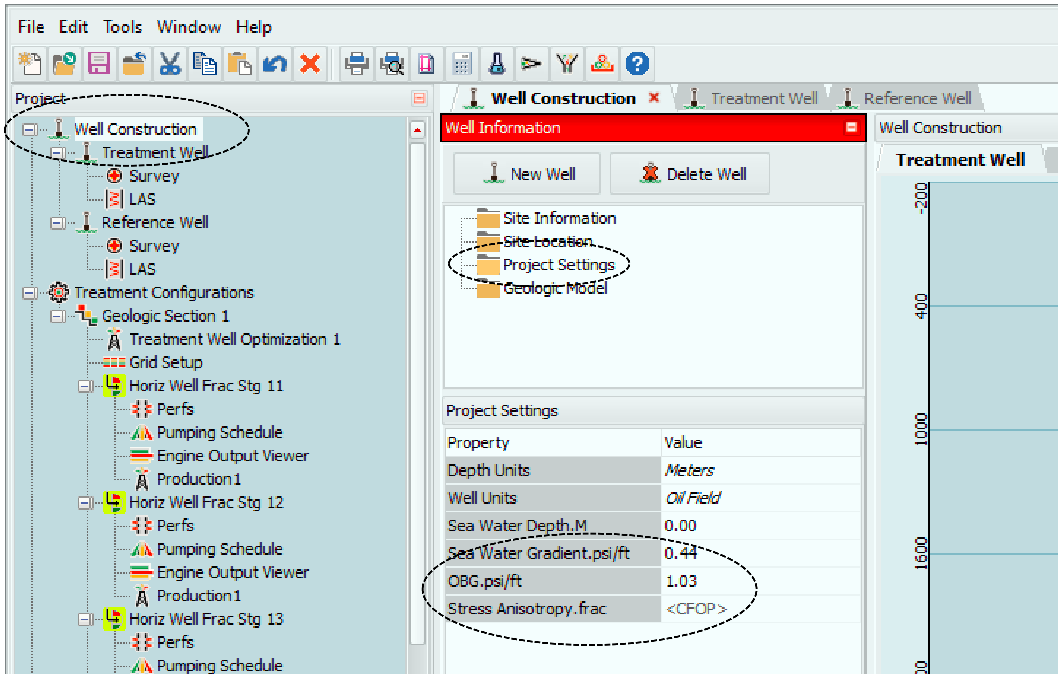


Check **Well Azimuth** and **Azimuth of Max Stress** in Well Construction: Azimuth of maximum stress of zero automatically sets it perpendicular to the well azimuth. Well azimuth of zero may be misinterpreted. Try to use the actual values and remember to Update Site Location.



Property	Value
Coordinate System	UTM
Easting.M	<Please Specify>
Northing.M	<Please Specify>
Elevation.M	<Please Specify>
UTM Zone	
Lat.dec	0
Lon.dec	0
Well Azimuth.°	0.00
Azimuth of Max Stress.°	0.00
Surface Map	

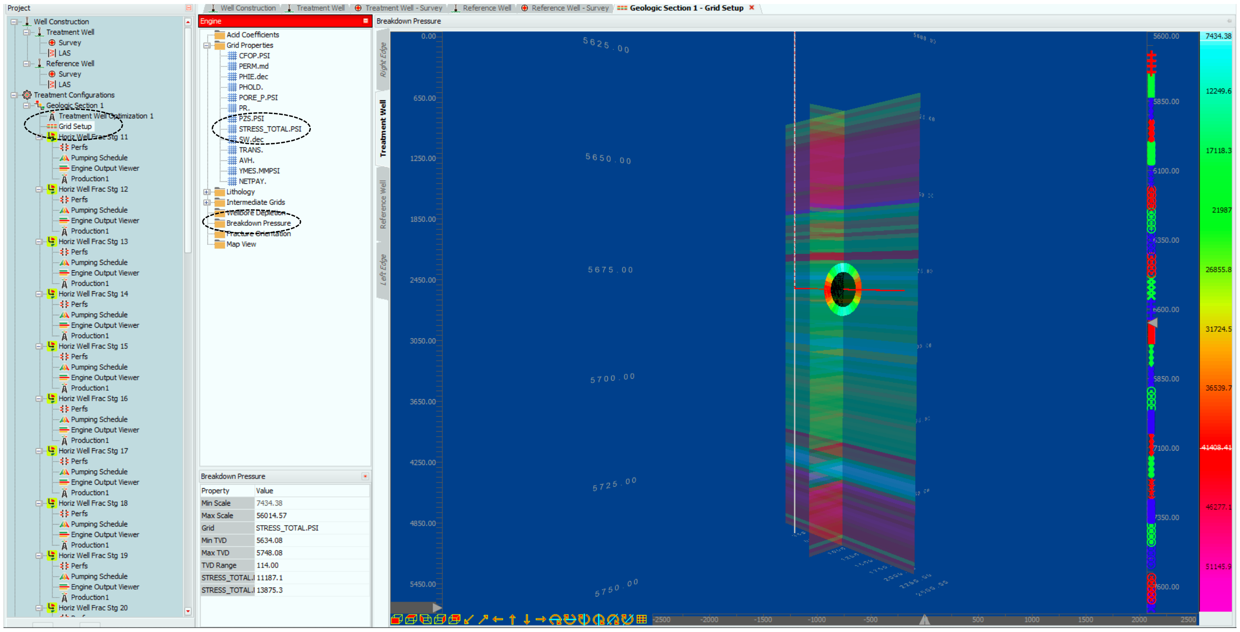
Check **Overburden Gradient (OBG) and Stress Anisotropy (CFOP is default)** in Well Construction-Project Settings:



Property	Value
Depth Units	*Meters*
Well Units	*Oil Field*
Sea Water Depth.M	0.00
Sea Water Gradient.psi/ft	0.44
OBG.psi/ft	1.03
Stress Anisotropy.frac	<CFOP>

In GOHFER v 9.3.0.65 and newer versions, some additional LAS and Grid curves have been added. These include ANIS.PSI for x-y stress anisotropy, and STRESS_MAX.PSI which is the maximum horizontal total stress. ANIS is defaulted to the CFOP curve or grid but can be scaled or manipulated separately. This allows the critical fissure-opening pressure to describe the opening of fissures that are not necessarily normal to the primary fracture. In this case, the actual maximum horizontal stress will be greater than CFOP+STRESS_TOTAL. STRESS_MAX will be displayed on the longitudinal grid in the Grid Setup display and in the 3D Breakdown Pressure view. The minimum in-situ stress (STRESS_TOTAL) will be shown on the transverse fracture planes.

Check **Grid Setup** in the **Breakdown Pressure** display for min and max tangential stress around the well. Any base grid can be selected to activate the display. The distribution of tangential stress around the wellbore is controlled by the relative magnitude of the three principal stress and the wellbore inclination and azimuth in the stress tensor.



Breakdown Pressure

Property	Value
Min Scale	7434.38
Max Scale	56014.57
Grid	STRESS_TOTAL.PSI
Min TVD	5634.08
Max TVD	5748.08
TVD Range	114.00
STRESS_TOTAL.I	11187.1
STRESS_TOTAL.I	13875.3