IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 7, Issue 3 Ser. I (May. – June. 2019), PP 17-24
www.iosrjournals.org

Caprock Integrity Analysis during Hydraulic Fracturing For Produced Water Disposal: A Case Study in Niger-Delta

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Abstract:*Caprock, or seal, acts as a barrier to migration of fluid or gas out of intended trap as a result of its low permeability and high capillary-entry pressure of its nature. Also, the existence of discontinuities in seal Lithology has an effect on the mechanical properties of the caprock. Analysis of caprock is critical in determining the rock properties of the sealing formation with respect to the zone to be fractured. The induced deformations within the fractured zone of the formation can potentially result in a damage zone within the caprock formation. The main objective of this paper was to determine the strength of the caprock to withstand applied pressure within the fractured zone. In order to achieve this, the mechanical rock property of the caprock (Uniaxial Compressive Strength, Young Modulus, Poisson's Ratio, Bulk Modulus etc) was determined from existing correlations and the well data provided. Also the in-situ stress around the formation was determined. From the analysis, the estimated rock properties showed that the caprock can withstand the imposed pressure at the fractured zone taking into account the Maximum Allowable Annulus Surface Pressure (MAASP) of the well.*
Keywords:*Caprock Integrity, In-situ stresses, Hydraulic Fracture*

Date of Submission: 20-06-2019 Date of acceptance: 04-07-2019

I. Introduction

The Caprock is Caprock is a stronger or more resistant type of rock which overlies a weaker or less resistant type of rock. In the context petroleum engineering, caprock is generalized to be any non-permeable formation that may prevent oil, gas, or water from migrating to the surface [1]. The caprock most times is shaly, consist of high clay content and low permeability rock. In some cases, it immediately overlies the pay zone of the reservoir while in other cases, there is a buffer zone between the caprock and pay zone [2, 15]. During petroleum exploitation, the caprock plays an important role in safeguarding against the hydrocarbon fluid, stimulating materials, and their mixture invading zones above the caprock. Often, these zones contain groundwater aquifers. It forms a flow barrier to the migration of CO2 and holds the CO2 within the reservoir by virtue of the capillary pressure difference across the reservoir and seal boundary. Some studies indicate that the predominant risk for caprock integrity is fracture flow [2]. The thickness, permeability and entry pressure are the parameters which determine the seal capacity [3, 4].

II. Stress

In rock mechanics, the concept of stress is very paramount in understanding the rock behavior. Generally, stress is defined as the ratio of force to cross sectional unit area. Mathematically, it is defines as

$$\sigma = \frac{\text{Force}}{\text{Area}} = \frac{\text{F}}{\text{A}} \qquad (1)$$

It is as a result of the internal resistance or reaction a body experiences due to external forces or load acting on it. Stress is not based on the body size or shape but due to the orientation of the body [5].

2.1 In-Situ Stresses

In-situ stress which can also be called far-field stress is the state of the stress of the rock formation in its equilibrium position, (i.e., before any drilling activity is carried out). These stresses are generally compressive in nature. They mutually perpendicular to one another and exist at any point in the subsurface. They are the overburden, maximum and minimal horizontal stresses [6].

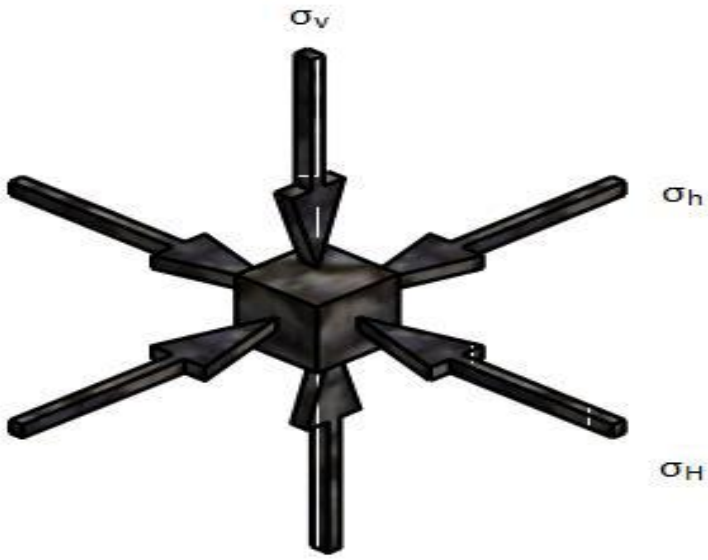

Figure 1: Orientation of In-situ stresses in a rock formation [6].

2.1.2 Overburden Stress

The overburden stress which is also called the vertical stress is as a result of the weight of overlaying rock matrices and the fluids in the rock pores. Due to Poisson's ratio effect, the weight exerted by the vertical stress component usually has the tendency to stretch and widen the rocks underneath in the horizontal lateral direction (Aiyeru 2014). The overburden stress can readily be calculated from the formula:

$$\sigma_v = \int_0^d \rho_b(h) g dh \quad (2)$$

d = the depth of the rock formation (ft),
g = constant due to gravity (32.175ft/s2)
h = the vertical height of the formation (ft)
σ_b = the bulk density of the formation (lb. /ft3)
All the parameters except the formation bulk density in the above equation can be gotten directly and at any depth.

2.1.3 Horizontal Stresses

The effect of Poisson's ratio tends to expand the rock formation underneath. However, the lateral expansion is also been confined and pushed back by the adjoining rock materials. This leads to the formation of horizontal stresses, which are referred to as the maximum and minimum horizontal stresses [5]. Ideally, it can be expected that the two horizontal stresses are equal. However, this is often not the case since natural effects such as uneven topography or faults results in uneven stresses. Natural phenomena like the earthquake make the stress to undergo changes because it is horizontal. The horizontal stresses are smaller in magnitude than that of the overburden in a relaxed lithology [6].

III. Geomechanical Studies

Sub-surface rocks are characterized by different stresses acting differently in terms of magnitude and azimuth. A geomechanical study was done on a well in Niger-Delta. This study consists of characterizations of in-situ stresses, pore pressure, rock strength, and rock mechanical properties of the zone of interest to determine the integrity of the rock to withstand the applied pressure in the fractured rock zone.

3.1 Importance of Geomechanics

Involving Geomechanics at the very beginning of field development planning allows risk reduction for reservoir stimulation, increase hydrocarbon recovery and enhance overall economic of the field. The rock mechanical properties of rocks are changed due to operations resulting from drilling, production or injection which alter the equilibrium of the rock formation. Such changes can seriously impact drilling operations, completions infrastructure, and production performance all of which can result in unexpected cost and time overruns [14]. Problems resulting from geomechanical issues are responsible for almost half of non-productive time (NPT) HPHT, deep water and other challenging environment [7, 14]. Without a strategy for avoiding or minimizing potential geomechanical problems, your project may cost millions more than budgeted. Today, most operators consider Geomechanics analysis and planning a necessary strategic component of exploration and field development activities. Identifying potential issues, planning for, and managing them saves time and improve safety at the wellsite.

IV. Rock Mechanical Properties

The knowledge of mechanical properties of a producing formation as well as the surrounding formations is extremely important to predict the shape and to calculate the dimensions of hydraulic fractures. These mechanical properties include Young's modulus, shear modulus, Poisson's ratio, bulk modulus and compressibility [8]. The calculation of the mechanical properties of the formation of zone of interest and the caprock was done using the following equations.

Unconfined Compressive Strength (UCS) for shale $=0.77x\left(\frac{304.8}{\Delta t}\right)^{2.93}$ Horsrud 2001 (3)

Unconfined Compressive Strength (UCS) for sand $= 1200Exp^{(-0.036\Delta t)}$ McNally, 1987 (4)

Compressional transit Time $V_p = \frac{1000000\ x\ 0.305}{\Delta_{tp}}$ (5)

Shear transit Time $V_s = \frac{1000000\ x\ 0.305}{\Delta_{ts}}$ (6)

Where

Δtp and Δts are the interval transit times recorded by the compressional and shear sonic logs respectively in µsec/ft

Young's Modulus $E = 2G(1+v)$ (7)

Shear Modulus $G = 1.34 * \frac{10^{10}\rho_b}{\Delta t_s^2}$ (8)

Poisson's Ratio $v = \frac{\frac{1}{2}\left({\Delta t_s}/{\Delta t_c}\right)^2 - 1}{\left({\Delta t_s}/{\Delta t_c}\right)^2 - 1}$ (9)

Bulk Modulus $K = 1.34 * 10^{10}\rho_b\left(\frac{1}{\Delta t_c^2} - \frac{4}{3\Delta t_s^2}\right)$ (10)

Compressibility $c_b = \frac{1}{k}$ (11)

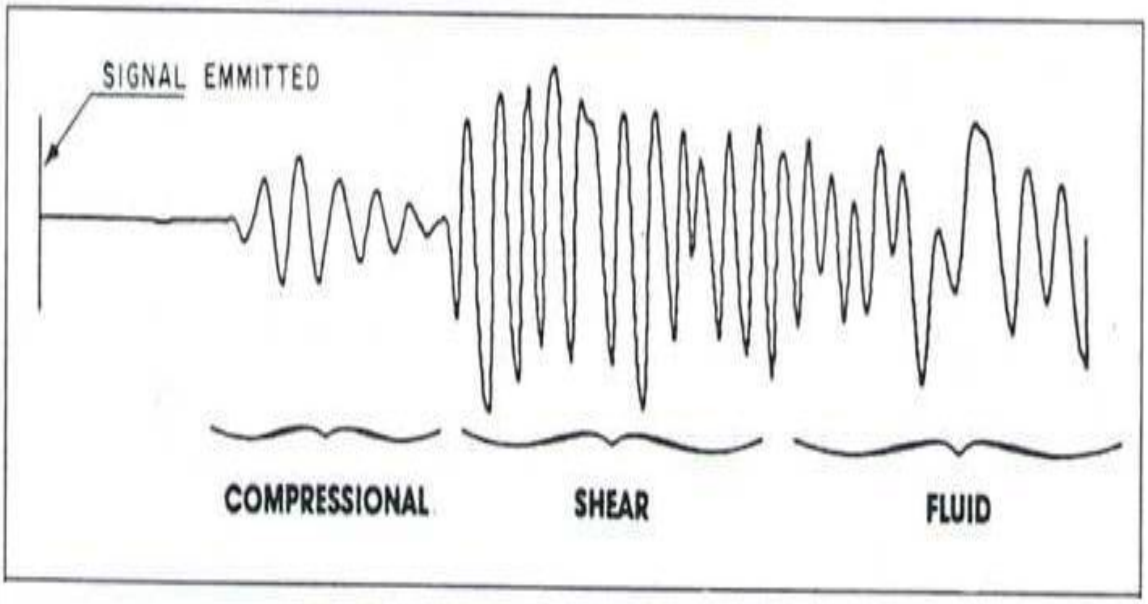

Figure 2: Typical sonic waveform in borehole [9]

The key to accurate determination of mechanical properties is an accurate measurement of shear wave travel time in the formation.

V. Fracture Gradient

The fracture gradient represents the slope profile of the fracture pressure in a rock formation. At any depth, the fracture pressure is the pressure required to initiate fractures in the formation. It is very important to be able to accurately estimate the fracture gradient of the formation in order to prevent lost circulation while drilling and it also has a direct influence on casing strings design. In drilling, the upper limit of the mud weight window is taken as the fracture gradient. The leak-off pressure (LOP) obtained from the leak-off test (LOT) is normally considered by the drilling engineers as the fracture gradient. Geomechanical engineers disagree and maintain that the fracture gradient should be the minimum horizontal stress [10]. Generally, fracture gradients can be determined by the following technique:

1. Experimentally or direct method.
2. Theoretically or indirect method.

5.1 Fracture Gradient Determination

The factor used to determine formation fracturing pressure as a function of well depth in units of psi/ft. The fracture gradient of the formation was calculated using the Ben Eaton's correlation [12]

$$F = \left(\frac{\sigma - P}{D}\right) x \left(\frac{v}{1 - v}\right) + \frac{P}{D} \quad (12)$$

Where
σ = overburden stress (psi)
ν = Poisson's ration

VI. Zone of Interest

The zone of interest consists of a top reservoir T-1 is at 5580 ft while the base is at 5780ft. The thickness to be fractured from the top to the base is 164ft. The zone of interest is a sand formation with intercalation shale. The sand is dirty sand with shale content within the zone above 70%. This could be responsible for the low permeability and porosity as observed in this zone.

Table 1: Geomechanical Properties of Zone of Interest

MD (ft)	TVD (ft)	Pp (psi/ft)	P_{frac} (psi/ft)	σ_v (psi/ft)	VSH (%)	UCS_{sand} (psi/ft)
5673	5580.14	0.433	0.748	0.919	6.02	0.326
5676	5583.14	0.433	0.778	0.912	62.63	0.210
5680	5587.14	0.433	0.698	1.017	56.75	0.875
5700	5607.14	0.433	0.683	0.935	67.75	0.708
5720	5627.14	0.433	0.657	0.904	0.00	0.788
5740	5647.14	0.433	0.665	0.981	33.36	0.992
5760	5667.14	0.433	0.669	0.931	7.13	0.787
5780	5687.14	0.433	0.680	0.957	5.11	0.796
5800	5707.14	0.433	0.666	0.948	13.13	0.859
5820	5727.14	0.433	0.651	0.927	12.15	0.903
5830	5737.14	0.433	0.706	0.986	41.10	0.706
5835	5742.14	0.433	0.705	1.031	65.77	0.849

VII. Integrity of Cap Rock

The overlying caprock is shale of about 28 ft from the base of the sand above it and the sand below it. The rock strength of the cap rock is determined in order to ascertain the stresses and the fracture gradient of the rock. The cap rock (shale) strength was calculated to ensure that it can withstand the stresses imposed by the pressuring fluid on the interval of interest. The UCS was computed using the 2001 correlation developed by Horsrud which is the correlation adopted by most oil and gas industries. The mechanical rock properties calculated is tabulated in tables 2 and 3 to ascertain if the caprock will be able to withstand the imposed pressure at the zone of interest.

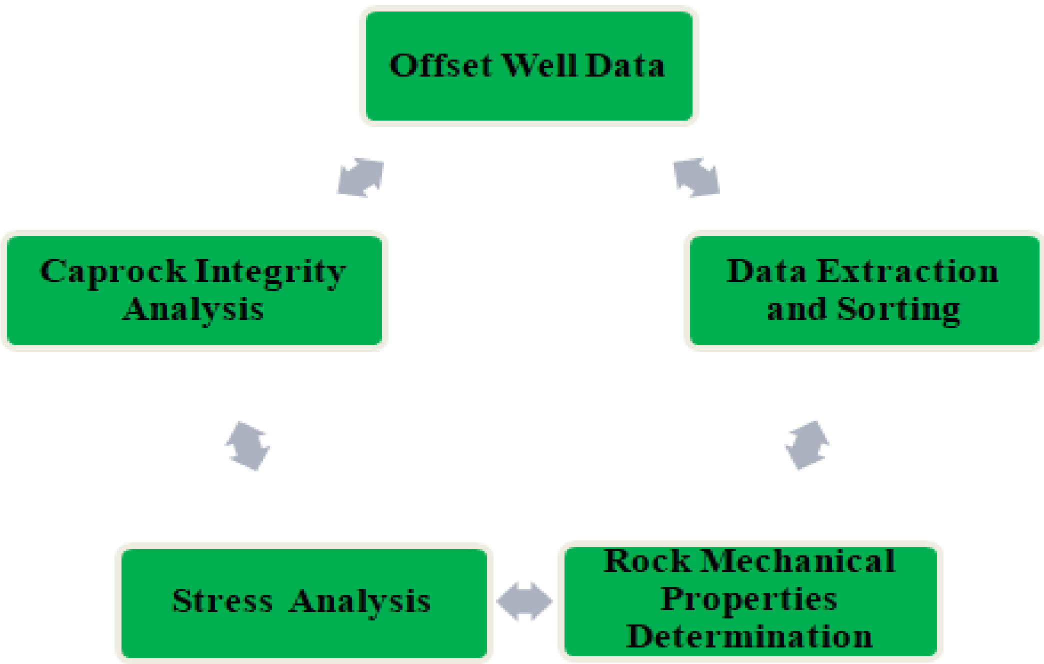

Figure 3: Workflow for Geomechanical Analysis

Table 2: Rock properties of the caprock

MD (ft)	TVD (ft)	Pp (psi/ft)	P_{frac} (psi/ft)	σ_v (psi/ft)	VSH %	UCS_{shale} (psi/ft)
5645	5552.14	0.433	0.648	0.911	12.80	0.549
5648	5555.14	0.433	0.710	1.000	38.21	0.474
5652	5559.14	0.433	0.763	0.908	25.81	0.223
5658	5565.14	0.433	0.724	1.023	73.03	0.464
5661	5568.14	0.433	0.748	1.025	76.42	0.402
5662	5569.14	0.433	0.759	1.018	74.33	0.367
5665	5572.14	0.433	0.667	1.022	36.60	0.666
5668	5575.14	0.433	0.668	0.991	20.47	0.530
5670	5577.14	0.433	0.682	0.947	1.97	0.479
5672	5579.14	0.433	0.682	0.929	3.38	0.448
5673.5	5580.64	0.433	0.748	0.891	4.74	0.227

Table 3: Geomechanical Properties of Zone of Interest and Caprock

Rock Type	σ_v (psi/ft)	P_{frac} (psi/ft)	ν	C_0 (psi)
Zone of Interest	0.856-1.026	0.642-0.786	0.290-0.422	1251
Caprock	0.891-1.040	0.697-0.881	0.277-0.417	1432

VIII. Fracture Orientation

The fracture pressure is the required pressure in the wellbore at which the formation will break open. When pressure at the wellbore exceeds the least stress within the rock formation, the formation will fracture. Normally, these fractures will propagate in a direction perpendicular to the least principal stress as depicted in figures 4, 5 and 6.

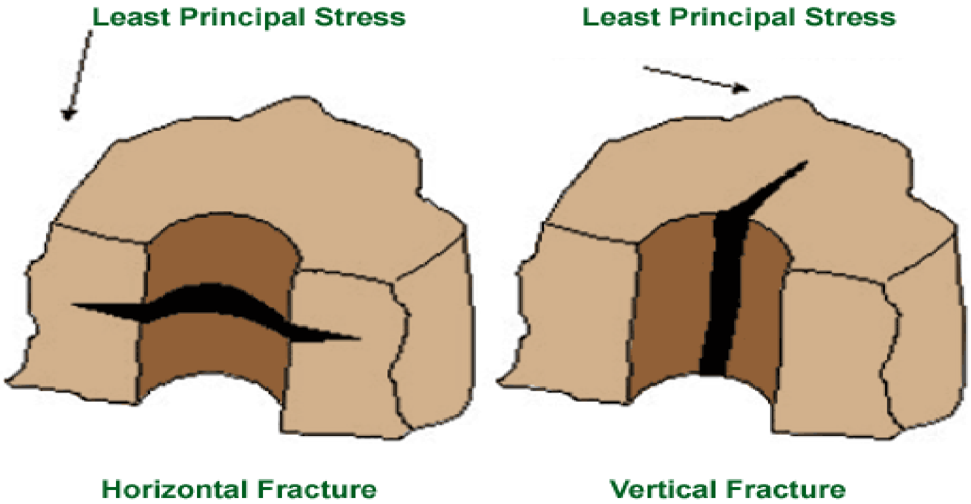

Figure 4: Diagram showing horizontal and vertical fractures in the direction of least principal stress [12]

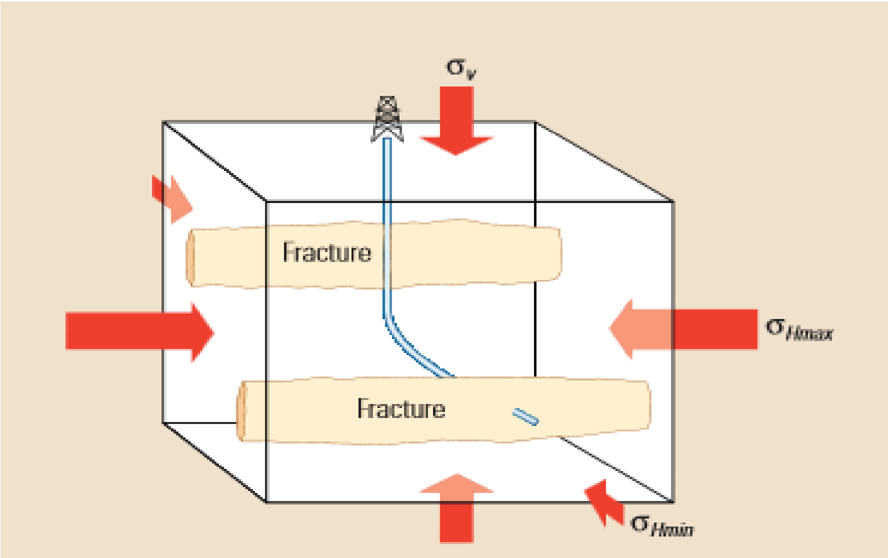

Figure 5: In-situ stresses and fracture orientation [13]

1.1 Fracture Propagation Orientation

The orientation and propagation of hydraulic fracture is controlled by the in-situ stresses within the subsurface formations. Hydraulic fractures are tensile fractures, and they open in the direction of least resistance. If the maximum principal compressive stress is the overburden stress which is the situation in this case, then the fractures are vertical, propagating parallel to the maximum horizontal stress when the fracturing pressure exceeds the minimum horizontal stress. Because hydraulic stimulation fractures open normal to the least principal stress, most fractures are vertical and propagate in the direction of the maximum horizontal in-situ stress. This area is a normal faulting environment typical of the Niger Delta. In fig. 6, the fracture propagation orientation is shown in the direction of the breakout based on data from the caliper log.

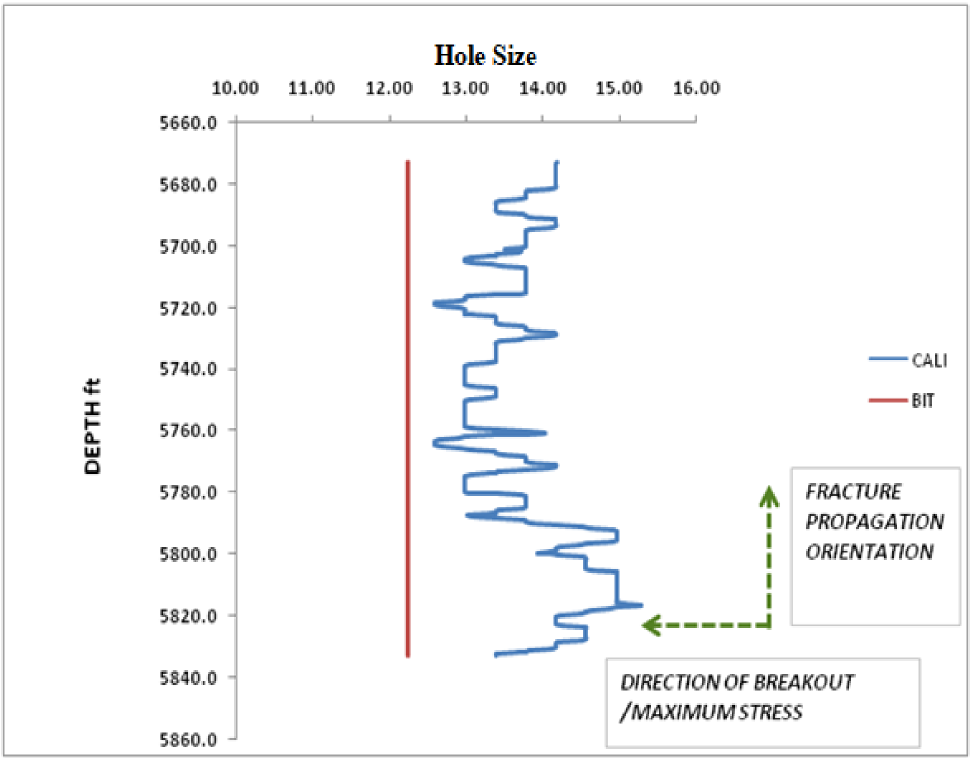

Figure 6: Fracture Propagation Orientation for field X

IX. Conclusions

The integrity of a caprock is a key feature during the hydraulic fracturing processes. A geomechanical study was done on field X to ascertain the integrity of the caprock to withstand the imposed pressure at the fractured zone. The well log data was used to determine the geomechanical parameters of the fractured zone and the caprock. The rock strength, overburden stress, fracture gradient, Poisson's ratio, Young modulus, Frictional angle and cohesion were determined. The caliper log of the well was used to determine the direction of the maximum in-situ stress thereby capturing the fracture orientation. Based on the geomechanical studies carried out, the following conclusion was reached:

1. Geomechanical study is critical and paramount in determining the integrity of the cap rock.
2. The fracture gradient of the caprock is within the range of 0.647 – 0.748psi/ft while the UCS ranges from 0.21 – 0.70 psi/ft.
3. The calculated parameters shows that the caprock is expected to with stand the imposed pressure within the fractured zone.
4. The hydraulic fractures are vertical due to the horizontally oriented nature of the breakouts observed in the well used as case study which is an indication of the maximum horizontal stress direction.

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