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Evaluating the Impact of Stress-Induced Changes on Caprock Integrity in the San Juan Basin.

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Abstract

Subsurface injection and long-term containment of carbon dioxide (CO2) in saline aquifers are crucial for mitigating climate change and transforming the energy landscape. To ensure safe containment, it is essential to investigate the geomechanical impacts of subsurface injection, particularly injection-induced stress on reservoir and caprocks. This research focuses on examining how these stresses affect the long-term structural stability of the caprocks and the integrity of the Entrada formation in the San Juan Basin. A model representing the formation of interest was constructed using geophysical log data and calibrated using injection and bottom hole pressure data of 22 nearby saltwater disposal (SDW) wells within the study area. 1D mechanical earth model along the stratigraphic well was integrated with 3D seismic elastic inversion data to generate a 3D mechanical earth model. A two-way coupled geomechanics-hydrodynamic simulation was performed incorporating the Kozeny-Carman stress-dependent permeability correlation to understand the changes in permeability and effective stress dynamics with the increase in reservoir pressure due to the CO2 injection. The capillary entry pressure and stress-strain responses of the caprocks were evaluated for risk assessment. The stress path, stress redistribution, critically stressed areas, and formation uplift caused by CO2 injection were identified. Analysis of the stress due to CO2 injection and capillary entry pressure indicate that some part of the cap rock is critically stressed. Stress-induced changes on the caprock integrity showed considerable increase in pore pressure shifting the Mohr circle to the left-side but staying below the failure envelope for the reservoir caprock interphase, indicating no rock failure. The capillary entry pressure was found to be sufficiently high preventing CO2 from penetrating the caprock thus ensuring that CO2 does not exceed the threshold required to compromise the seal. The results show a considerable reduction in effective stress and displacement within 1 mile from the injection point. Additionally, the results highlights that the northwestern section of the caprock experiences the highest stress. While stress changes affect pore pressure and deformation, caprock integrity remains intact ensuring safe CO_2 containment. This study presents a detailed analysis of the geomechanical effects of CO_2 sequestration on stress redistribution within the caprock and caprock mechanical properties dynamics within the San Juan Basin. It evaluates

the long-term geomechanical behavior of the caprock with particular attention to stress-induced deformation and integrity.

Introduction

The primary contributor to the increasing concentration of carbon dioxide in the atmosphere is the combustion of fossil fuels. Activities involving hydrocarbons and industrial processes contribute to global warming and climate change through emissions released worldwide (Nunes, 2023). Research indicates that an additional 30 billion tons of CO_2 are added to the atmosphere globally each year (Friedlingstein et al., 2022). This has led to the development of geological CO_2 storage as a growing field of study, aiming to create a cleaner environment by minimizing greenhouse gas emissions. Fluid management in underground storage must address challenges such as environmental concerns and rheological performance (Duartey et al, 2023). The three main alternatives are: depleted oil and gas fields, saline formations and un-mineable coal-beds (Eigbe et al,2023). Injecting carbon dioxide into deep geological formations increases the pore pressure within the reservoir and caprock potentially inducing fractures or reactivating faults within the storage formation (Zoback, 2010). These induced fractures and potentially activated faults could act as conduits allowing CO_2 to migrate from the reservoir and risking leakage into shallower formations or even the atmosphere. The San Juan Basin, located in northwestern New Mexico, is the selected site under the San Juan CarbonSAFE project, a commercial-scale CO2 sequestration project sponsored by the USA Department of Energy to address climate change issues. Potential sequestration targets in the basin are the Jurassic Entrada and Bluff sandstone deposits, while the Brushy Basin, Summerville formation and Todilto formation are the major confining zones. For this project only the Entrada formation is considered for sequestration of 50Mt of CO2 over the period of 30 years. To ensure the accuracy of reservoir simulations, it was validated by accurately reproducing the historical behavior of the reservoir by adjusting reservoir parameters to match historical SWD data. This study investigates the interplay between stress-induced effects and porosity-permeability dynamics during CO_2 injection cycles, using a two-way coupling geomechanics-reservoir model to analyze formation behavior under varying stress conditions.

Theory and Methodology

This study specifically focuses on the coupled hydrodynamics and geomechanical simulation to investigate stress impacts on reservoir properties by integrating hydrodynamic geomechanical processes. The section seeks to outline the steps to analyze the effects of injection-induced stress on cap rock integrity within subsurface formations. The size of the model extends within a 40x40 miles area with grid cells 143x144x37 in the I, J, K directions, forming a total of 761904 grid cells. Each grid cell within the model has a lateral dimension of 1500 feet by 1500 feet, ensuring a high level of spatial detail. The vertical stratification of the model includes thirty (30) geological layers, which are designed to capture the complexity and heterogeneity of the subsurface geology. The injection zone is the Entrada formation with Summerville as the primary caprock. History matching was performed using 22 SWD wells. The base case simulation data for most of the wells did not match the observed data, hence there was a need to adjust most of the parameters in order to achieve a reasonable match. In do this a thorough sensitivity analysis was performed to study the most sensitive reservoir parameters on pressure behavior in the observation well. The results of the sensitivity analysis showed that permeability and relative permeability were the most sensitive parameters. The permeability was adjusted without exceeding the maximum permeability of geological model. The relativity permeability was adjusted accordingly and a good match was achieved. The furcating phase was conducted with 50Mt of CO2 injected over thirty years. To investigate the geomechanical impact of the injected CO2, a geomechanical grid was built independently with the reservoir grid for a two-way coupled modeling. This functionality is designed to incorporate underburden, overburden and sideburden layers into the original reservoir grid. To ensure structural integrity, the model is designed with a sufficient thickness of stiff bedrock to minimize the risk of buckling. This stiff rock layer provides the necessary structural support for the reservoir model. The completed geomechanical grid, incorporating all necessary adjustments, is shown in Figure 1 and 2 showing the coupling process. The normalized Kozeny-Carman stress-dependent permeability correlation was used to understand the changes in permeability and it is expressed as:

$$k = \left(\frac{1}{f_g \tau S_{vgr}^2}\right)\frac{\varnothing^3}{(1-\varnothing)^2}$$

k : Permeability (μm^2)

f_g : Shape factor

τ : Tortuosity

$\varnothing$: Effective porosity

S_{vgr} : Specific surface area of the grain size in μm^{-1}

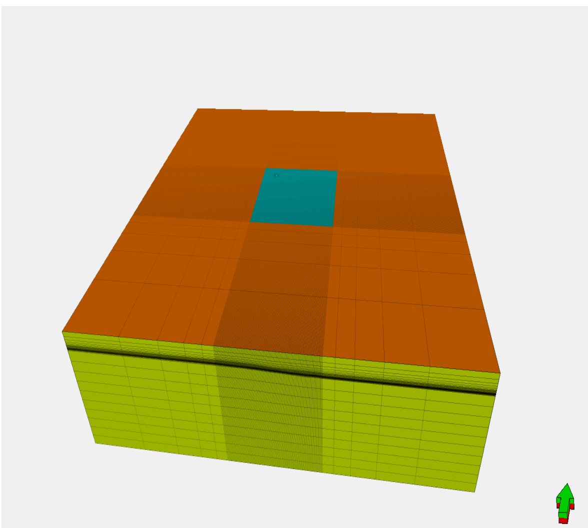
$$[K] = [K_o]\frac{\varnothing^3/(1-\varnothing)^2}{\varnothing_o^3(1-\varnothing)^2}$$

K_o : Initial Permeability (md)

K : Updated Permeability (md)

$\varnothing_o$: Initial Porosity

$\varnothing$: Updated Porosity



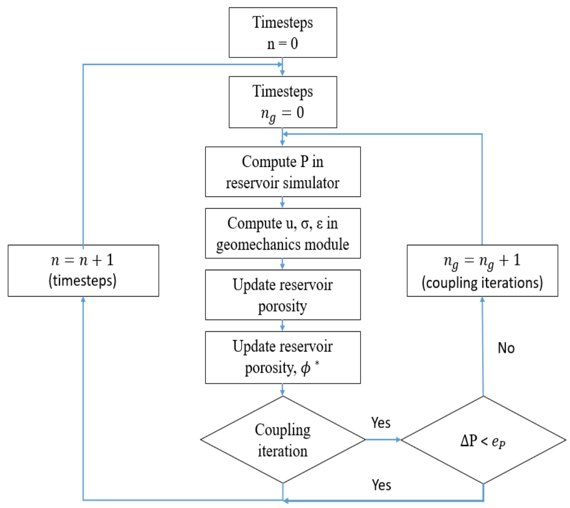
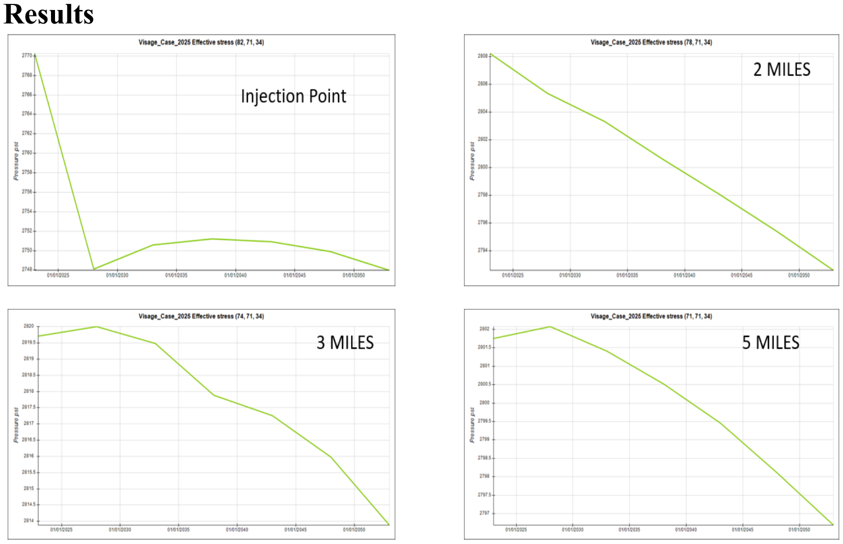


Figure 1: Final Geomechanical Grid of Model Figure 2: Generalized flow diagram for iterative coupling (after Tran et al. 2009b)

Results



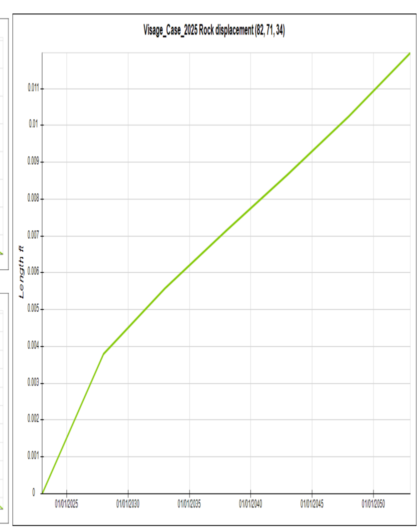
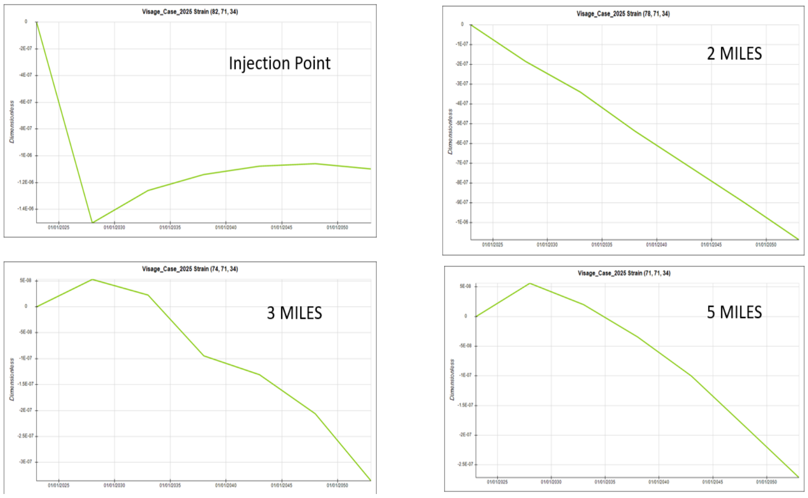


Figure 3: Effective Stress of the Caprock at different location Figure 4: Rock Uplift of the Caprock



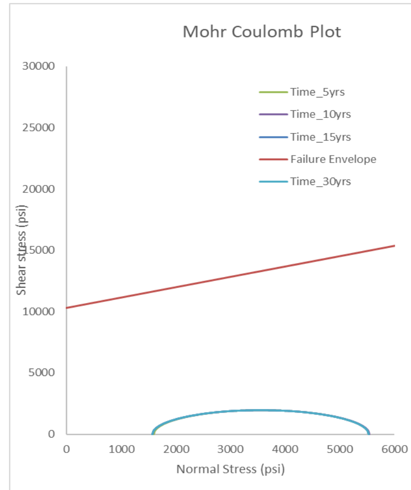


Figure 5: Strain at different location of the Caprock

Figure 6: Morh Circle showing deformation at different Time step of the Caprock

Discussion

According to the loading stress path, there are two different ways to define rock under pore pressure increase (Nauroy 2011): At low mean effective stresses, the rock rapidly loses the ability to resist the load and begins to deform; in another words, brittle failure along the formation of a shear band crossing the rock. At high mean effective stresses, the rock maintains the ability to resist the load as the strain due to slip along a multitude of intersecting shear planes is increased; in another words, ductile failure occurs under the effect of homogeneous micro-cracking. Figure 3 shows the decrease in effective stress at different location during the whole injection period. The reduction is more pronounce at the injection point compared to moving away from the injection point. The reduction in effective stress resorts in deformations of the rock as illustrated by Figure 5 and the strain recorded are in micro-strain. Figures 3,4,5,6, 9 and 10 show the stress path and standard Mohr's failure envelope for the caprock. The uplift record due to the CO2 injection is very minimal as illustrated by Figure 4. There is movement of the Mohr circles from right side to the left side due to stress redistribution as shown by Figure 6, representing a reduction in effective stress without significant changes in shear stress or rock failure (Zoback, 2012). This movement is very little due to the smaller reduction in effective stress during the injection period. As long as the stress remains within the elastic regime and the Mohr's circle does not intersect the failure envelop, no permanent deformation is seen even after the observation period. Most part of the caprock were not critically stress by the stress redistribution hence, the mechanical strength of the caprock resisted fracturing or plastic deformation which can create leakage pathways for CO_2. The northwestern part of the caprock is critically stress as shown by Figure 10 but there is no permanent failure after the CO2 injection. The high capillary entry pressure ensures that the caprock maintains its sealing capacity, preventing CO_2 from entering the pore spaces.

Conclusions

Effective stress decreases due to pore pressure increase but the rate of reduction decreases moving away from the injection well. Strain recorded within and after the 30 years of injection is in micro-strain magnitude. There is permeability update within the caprock but the increase in permeability is very small and no change was seen moving away from the injection well. The analysis of the Morh circle model shows a stable seal after 30 years of injection. Thirty years of monitoring the CO2 injection shows the seals is not compromised and the stress on the Caprock is reduced. This shows that the CO2 operation can be carried out without any geomechanical severe impact.

References

Nunes, L. J. (2023). The rising threat of atmospheric CO2: a review on the causes, impacts, and mitigation strategies. *Environments*, *10*(4), 66.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C., Hauck, J., ... & Zeng, J. (2022). Global carbon budget 2021. *Earth System Science Data*, *14*(4), 1917-2005.

Eigbe, P. A., Ajayi, O. O., Olakoyejo, O. T., Fadipe, O. L., Efe, S., & Adelaja, A. O. (2023). A general review of CO2 sequestration in underground geological formations and assessment of depleted hydrocarbon reservoirs in the Niger Delta. *Applied Energy*, *350*, 121723.

Zoback, M. D., & Gorelick, S. M. (2012). Earthquake triggering and large-scale geologic storage of carbon dioxide. Proceedings of the National Academy of Sciences, 109(26), 10164-10168. https://doi.org/10.1073/pnas.1202473109

Zoback, M.D., 2010. *Reservoir geomechanics*. Cambridge university press.

APPENDIX

1 D MEM

- The static Young's modulus was calculated using the modified Morales correlation, while the static Poisson's ratio was considered equivalent to the dynamic Poisson's ratio. The friction angle was estimated using Plumb's grain volume model, and the unconfined compressive strength was determined through the Coates-Denoo model. These methods yielded results that aligned well with those obtained from core samples, requiring no additional modifications.
- vertical stress gradient was calculated as 1.04 psi/ft by integrating the bulk density of the formation from the surface down to the Entrada Formation. The pore pressure within the Entrada Formation was estimated at 3604 psi, corresponding to a gradient of 0.434 psi/ft.
- The maximum horizontal stress orientation was identified as 45 degrees northeast, based on the analysis of drilling-induced tensile fractures observed in borehole imaging.
- Two models with differing assumptions were integrated to estimate the minimum horizontal stress. The linear elastic poroelastic horizontal strain model was applied to the higher-strength formations, while the Mohr-Coulomb failure model was utilized to describe layers in the overburden that are critically stressed. Certain zones exceeded the elastic range of the poroelastic horizontal strain model but had not yet reached the critical stress threshold defined by the Mohr-Coulomb model. For these elastoplastic layers, an average of the two models was used. The minimum horizontal stress gradient in the Entrada Formation, assuming normal pore pressure, was determined to be 0.65 psi/ft.

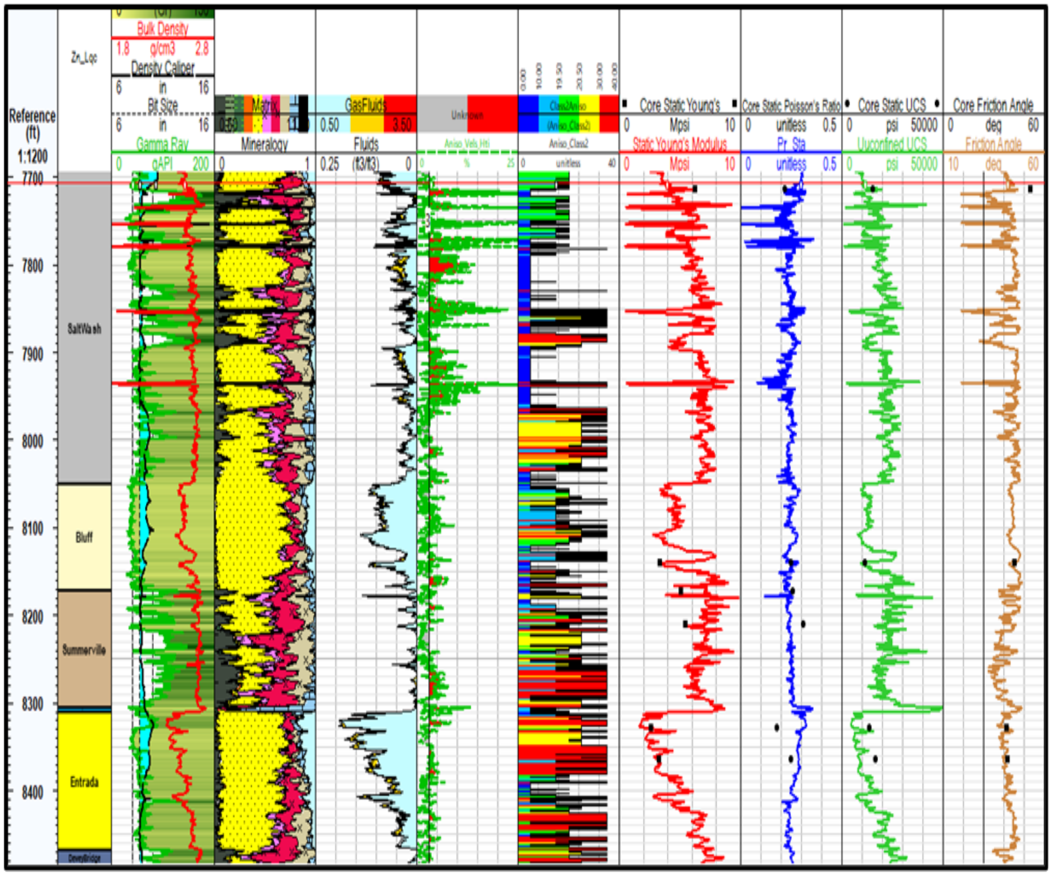


Figure 7: Stratigraphy correlated with Mechanical strength from logs and core

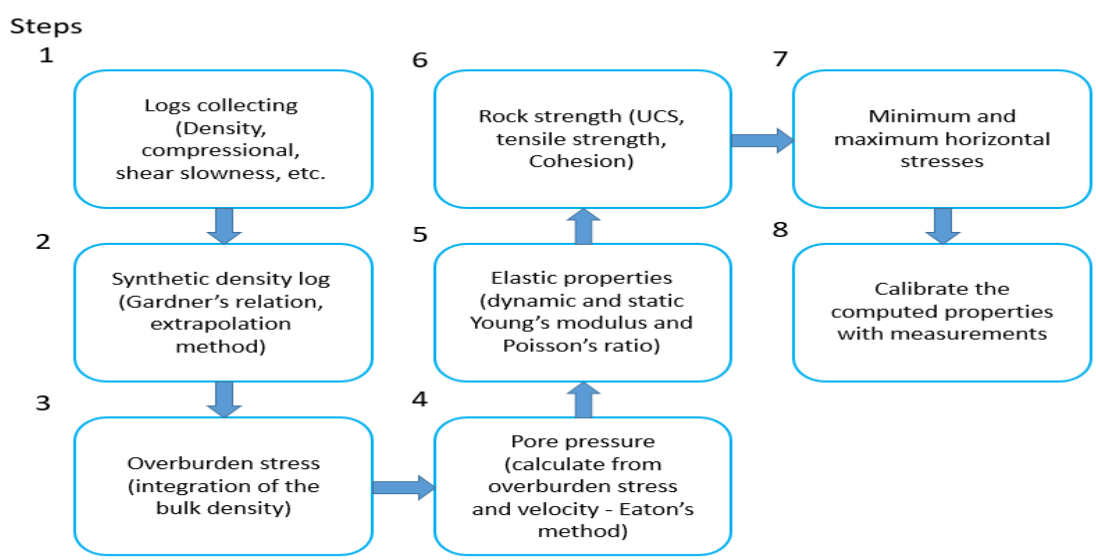
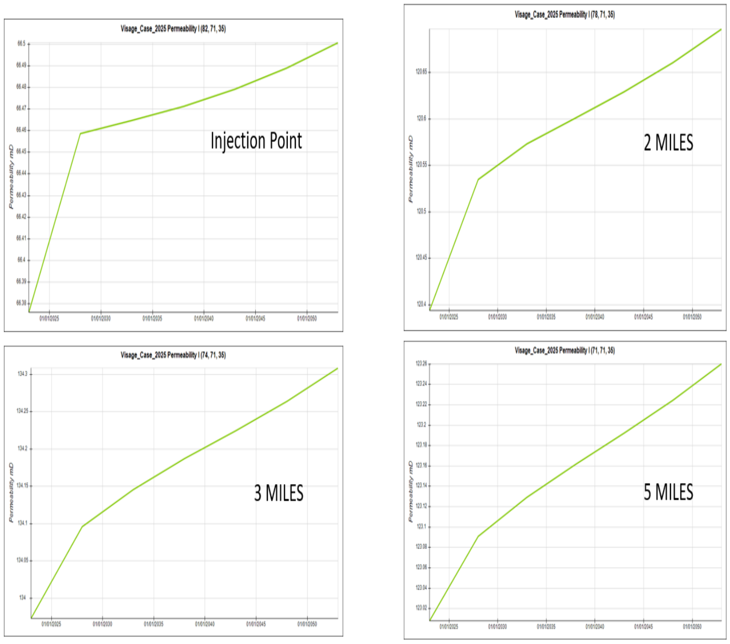


Figure 8: Schematic workflow of 1D MEM (after Bui et al. 2023)



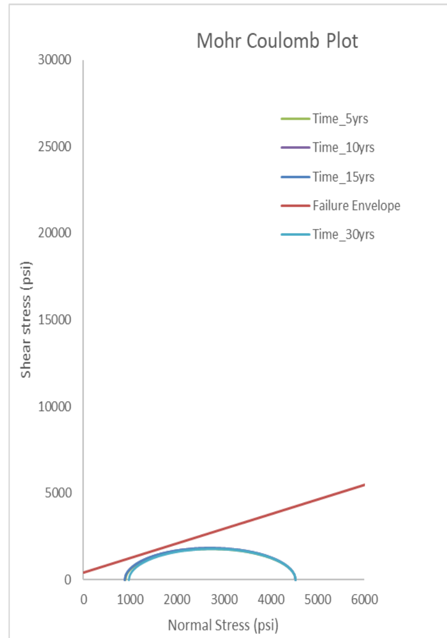


Figure 9: Permeability update at different location from the injection point

Figure 10: Morh circle of North Western part of the Caprock been critically stress.

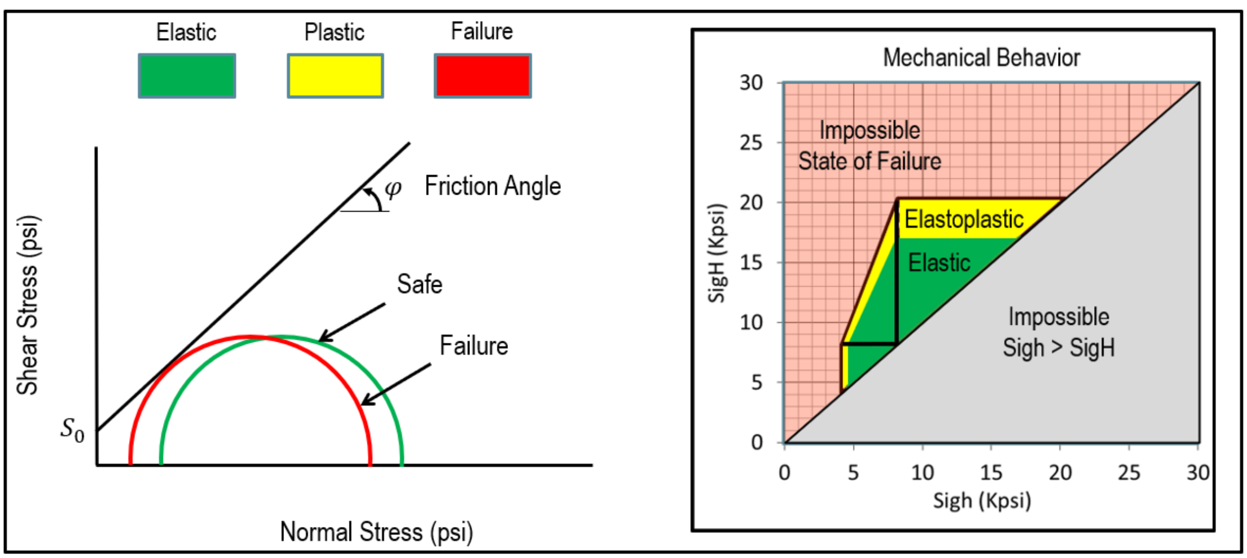


Figure 11: Analysis of stress polygon. The left diagram illustrates a standard Mohr-Coulomb plot. A black linear failure envelope defined by the cohesion and friction angle.