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Evaluation of CO_2 Storage Site Using Fault Seal Assessment Within the Niger Delta Field

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Introduction

Greenhouse gases pose significant dangers due to their constant emissions into the atmosphere. The greenhouse effect occurs when these gases trap heat close to the Earth's surface. Throughout Earth's history, the climate has undergone continuous warming and cooling (Cermak, 2024). Natural processes, such as volcanic eruptions, release gases and particles into the atmosphere, while tectonic plate movements alter the positions of land masses, affecting wind and current patterns (Audi et al., 2020). Since the industrial revolution which marked the rise of industrialization and construction, levels of greenhouse gases in the atmosphere have increased leading to a rise in earth's temperature (Soeder, 2025; Audi et al., 2020). However, human activities add extra heat and greenhouse gases to the atmosphere, exacerbating global warming. Historically, natural climate fluctuations followed predictable patterns but recent changes are occurring at much faster rates due to human influence (Gambhir et al., 2021; Raji et al., 2022).

Studies have revealed that carbon dioxide (CO_2) as a gas remains in the Earth's atmosphere for extended periods years, decades, unlike methane, which dissipates relatively quickly (Shahbazi & Nasab, 2016). Carbon capture and storage (CCS) have emerged as a crucial process to address CO_2 emissions. CCS involves separating CO_2 from other gases, transporting it via pipelines or ships, and storing it in geological formations.

The natural accumulation of CO_2 has garnered considerable interest, as these reservoirs serve as analogues for studying underground CO_2 storage. By examining these natural CO_2 reservoirs, referred to as natural analogues, we can better select sites for underground storage and understand how CO_2 behaves when injected into geological formations. Identifying appropriate CO_2 storage sites is critical, with saline aquifers and depleted oil and gas reservoirs being the primary options. Several natural CO_2 reservoir analogues show that similar structural and trapping mechanisms may contain CO_2 in natural oil and gas traps, which have been depleted by drilling and oil production activities. It was important to look at field data and oil well data, in known sites, and use the information from them to apply in the current seal integrity and connectivity analysis. (Nosike, 2019).

Caprock acts as the main sealing system for CO_2 storage in geological formations. While the hydrodynamic sealing capacity of caprock has frequently been discussed in terms of hydrocarbon

migration, fewer studies have focused on its sealing capacity for CO_2 storage. Most existing storage projects utilize similar evaluation methods and indicators (Raji et al., 2022) to identify suitable CO_2 storage sites, specifically saline aquifers and depleted oil and gas reservoirs (Mohajan, 2017). The relationship between caprock and faults can be quite complex; therefore, a fault system's sealing ability must be thoroughly assessed before selecting suitable sites for CO_2 storage.

A lot of research and projects have been conducted on CO_2 storage in countries such as Algeria, Saudi Arabia, Norway and Canada etc and led by international organizations and oil company such as Sonatrach, Saudi Aramco, Staoil and Petroleum Technology Research Centre (PTRC) in some natural gas fields and oilfield around the globe.

This work evaluates the basins and fields suitable for carbon capture and storage. To achieve successful containment of CO2 subsurface, various critical conditions must be met to prevent any potential leakage back into the atmosphere, and these conditions are mainly in the subsurface and depend on the site's geology. The Niger Delta region has a high potential for carbon storage in depleted reservoirs. Hence, this study is aimed at determining and estimating the fault throw and depth at which CO_2 can be stored by conducting a fault seal assessment in the reservoir oilfield of the study area. Also, we will use the shale gouge ratio as an indicator to identify leaking and sealing faults. The study area will focus on part of the XY field within the Niger Delta Basin, which has a subaerial area of approximately 75,000 km², a total area of 300,000 km², and a sediment fill of about 500,000 km^2**.** Niger Delta Basin is situated on the West African continental margin in the Gulf of Guinea**.**

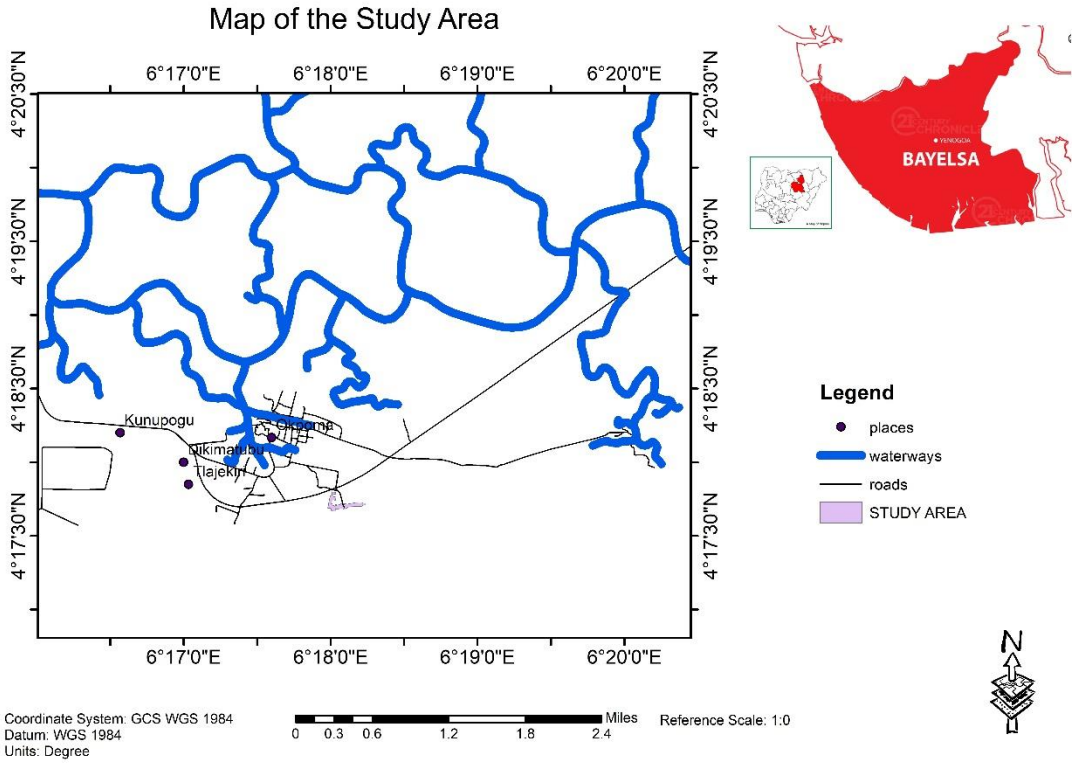


Fig 1: Map of Niger Delta showing the location of the Study Area

Evaluation Methods:

Fault Seal Assessment:

Fault assessment and analysis play an important role in understanding the characteristics and behavior of subsurface reservoirs and optimizing hydrocarbon exploration strategies (Jones & Hillis, 2003). Faults can be found in various geological settings and may serve as conduits or barriers to fluid flow within a reservoir (Roy et al., 2024). Therefore, analyzing the sealing potential of faulted cap rocks and the integrity of these fault zones is essential for reservoir characterization, risk assessment, and reservoir management. In this study, we focused on the risk assessment of faults in the study area. Fault seal assessment involves evaluating a fault's ability to prevent or allow fluid flow across it (Samson & Akinbode, 2020). Fault seals can influence the distribution, migration, and trapping of hydrocarbons. By conducting fault seal analysis, we can enhance reservoir development by determining the connectivity and pressure within different reservoir compartments and the risks associated with cross-fault or along-fault fluid movement (Ogilvie et al., 2020).

The application of fault assessment in CO_2 storage has become a topic of interest for geologists and engineers who aim to evaluate the feasibility and safety of identifying effective and sustainable CO_2 reservoirs in deep geological formations. Typically, a reservoir for CO_2 storage is located at depths greater than 800 meters, often covered by multiple caprock layers (Bashir et al., 2024). The uppermost caprock layer acts as a leakage-controlled layer and defines the extent of the sealing system that must be assessed. Caprocks are frequently interrupted by faults due to natural events such as earthquakes, volcanic eruptions, and explosions, resulting in various fault patterns (Chen et al., 2025).

Figure 2 presents a conceptual representation of a caprock-fault system used in CO_2-EOR (carbon-dioxide enhanced oil recovery) storage. It shows how the integrity of the caprock is related to different fault types, highlighting their importance for the safe storage of CO_2 in underground reservoirs (Bai et al., 2017). There are the embedding type, lower broken type, and broken-through type. The embedding type refers to direct caprocks only partly penetrated by the fault (fig. 2-a). The lower broken type refers to a direct caprock cut through by a fault, although the overlying caprock has not been reached (fig 2-b).

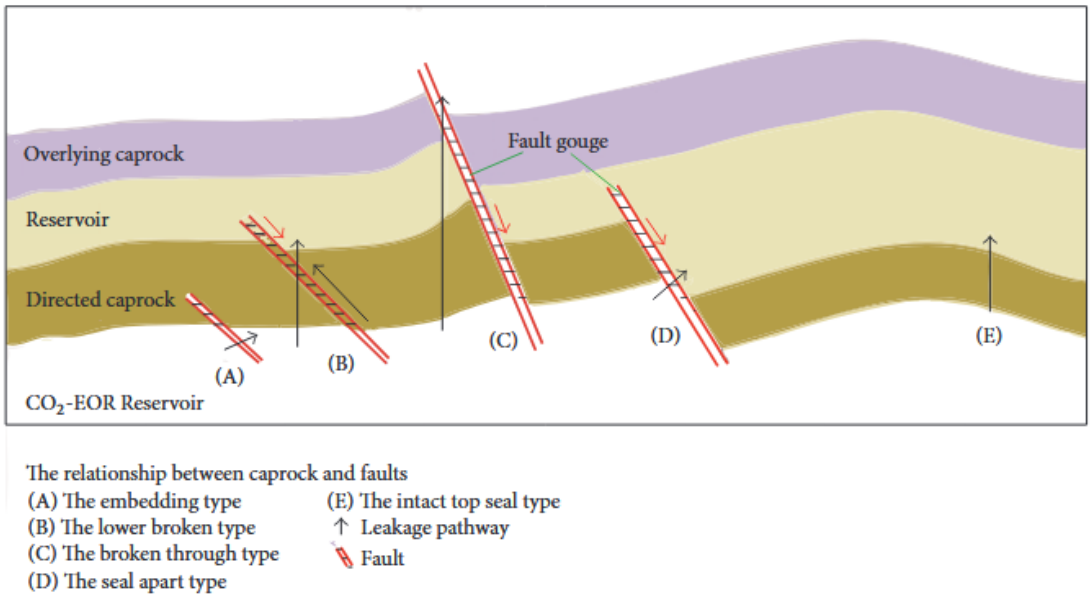


Fig. 2: Conceptual illustration of caprock-fault system types and their implications for CO_2-EOR storage integrity

The broken-through type refers to a direct caprock and its overlying caprocks that have been cut through by a fault (fig 2-c). The relationship between the fault-throw and the thickness of the direct caprock can also characterize the matching types between caprocks and faults. The following three matching types have been defined: intact top seal type, seal connected type, and seal apart type. The intact top seal type corresponds to an embedded type when faults do not penetrate the top of the direct caprock. The seal-connected type refers to a direct caprock that a fault has cut through, but the throw is less than the thickness of the direct caprock. The seal apart type refers

to a direct caprock that a fault has cut through, but the throw is greater than the thickness of the direct caprock (fig 2-d) (Chen et al., 2024; Bai et al., 2017).

Shale Gouge Ratio:

Shale gouge ratio (SGR) is a parameter used in fault seal analysis to estimate the potential for fault sealing based on the relationship between the thickness of shale gouge material and the fault throw (Yielding, 2002). SGR is calculated by dividing the volume of clay by the fault throw. The SGR provides an indication of the sealing potential of shale gouge within fault zones. A higher SGR suggests a greater volume of clay relative to the fault throw, indicating a higher likelihood of effective fault sealing (Bretan et al., 2003). The following steps are used to determine the shale gouge ratio

- Measure the thickness of shale gouge
- Calculate the fault throw
- Determine the volume of clay
- Calculate the SGR

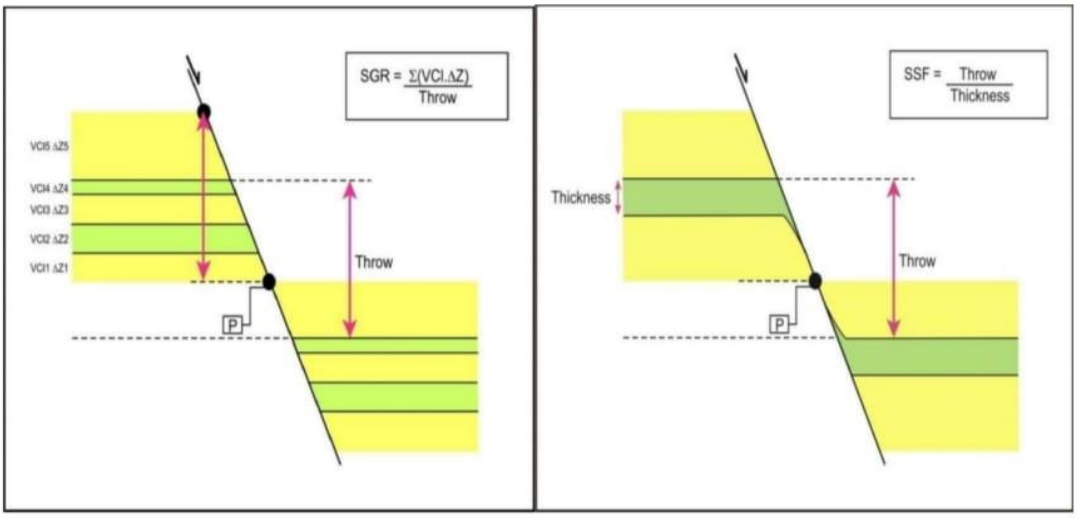


Fig.3: Illustration of SGR (Harris et al., 2002)

In the analysis of the shale gouge ratio (SGR), we are examining the net shale content within a specified throw interval to gain insights into the shale distribution within the geological formation (Freeman et al., 1998). This is a critical parameter in understanding the potential sealing capacity of the fault and assessing the reservoir and seal risks. The process involved mapping out the throw values along each fault and then normalizing them within contrasting colors based on the degree of throw displacement (Bretan et al., 2003). This visualization used a contrasting color scheme to represent different throw magnitudes. When the length of the reservoir is less than the fault throw it indicates fault sealing. It is represented with the color red. Conversely, if the fault shows no evident displacement (likely a fracture), it is represented in green indicating its fluid transmissibility potential. For fault throws with intermediate displacement along the reservoir

column, a yellow color is used to represent them. The gradient fill feature in MS Excel was utilized to normalize the throw data and enhance the visual representation of the fault throws.

Step 1: Determine the net shale content in relevant intervals: Our goal is to calculate the net shale content within the 0 m, 100 m, 200 m, and 300 m throw.

Fault Seal Analysis Using SGR

The shale gouge ratio (SGR) is calculated to quantify the clay smear within fault planes. The formula for SGR is:

$$\text{SGR (\%)} = \sum \frac{\sum(V_{shale} \times h_{shale})}{T_{throw}} \times 100$$

Where:

- V_{shale} = Volume fraction of shale at each interval
- h_{shale} = Thickness of the shale interval
- T_{throw} = Total fault throw

A higher SGR (> 0.4 or 40%) suggests effective fault sealing due to higher clay content.

Step 2: Net Shale Calculation

Net shale thickness is derived as:

$$\text{Net Shale} = V_{shale} \times h_{interval}$$

For a throw depth, total net shale is the sum of net shale across all intervals:

$$\text{Total Net Shale} = \sum_{i=1}^{n} V_{shale,i} \times h_i$$

Then, SGR at each throw depth is:

$$\text{SGR} = \frac{Total\ Net\ Shale}{Throw\ Depth}$$

The calculation was done manually, alternatively, it can easily be computed using the Excel spreadsheet software. The varying depth is plotted against the SGR at different throws. This takes the average of the V shale across the subintervals of corresponding throws. (Nosike, 2019).

Data Acquisition and Processing

- Well logs from three exploration wells were analyzed for Vshale using gamma-ray log interpretations.
- 3D seismic data were interpreted to delineate fault patterns and horizon correlations.
- Fault throws were extracted from structural maps.
- Microsoft Excel was used to compute SGR at various fault throws (0 m, 100 m, 200 m, and 300 m).

Results:

This dataset presents shale gouge ratio (SGR) fractions calculated at fault throws of 0 m, 100 m, 200 m, and 300 m across vertical depths ranging from 1000 m - 2600 m. The SGR threshold of 0.5 is used as a benchmark:

- SGR > 0.5 → shale-dominated fault gouge → good or effective seal
- SGR< 0.5→sand-dominated fault gouge →poor seal or transmissive

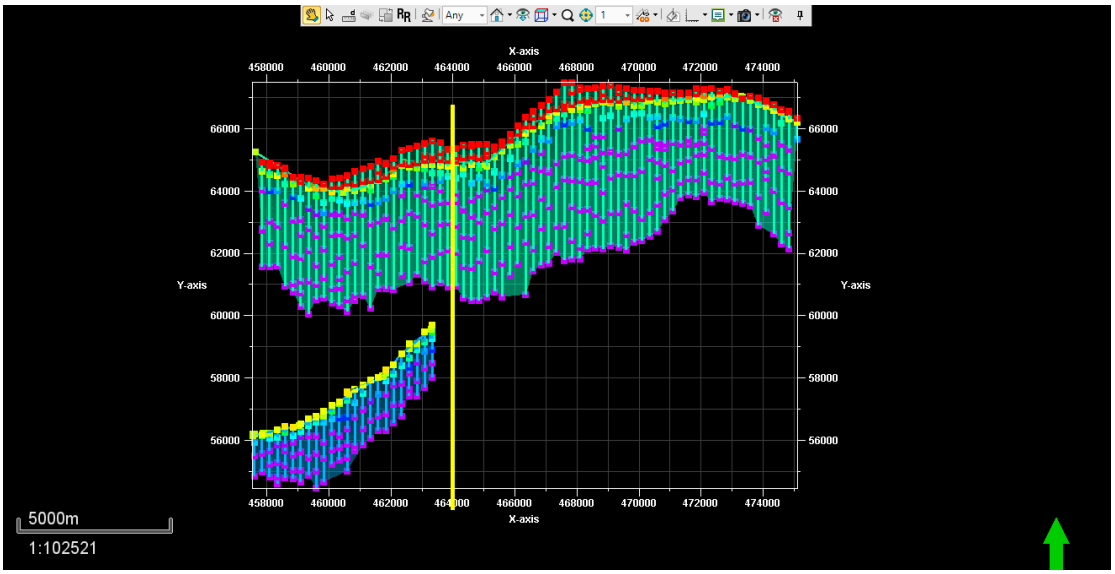


Fig. 4 (a): Interpreted Fault sticks in 2D view.

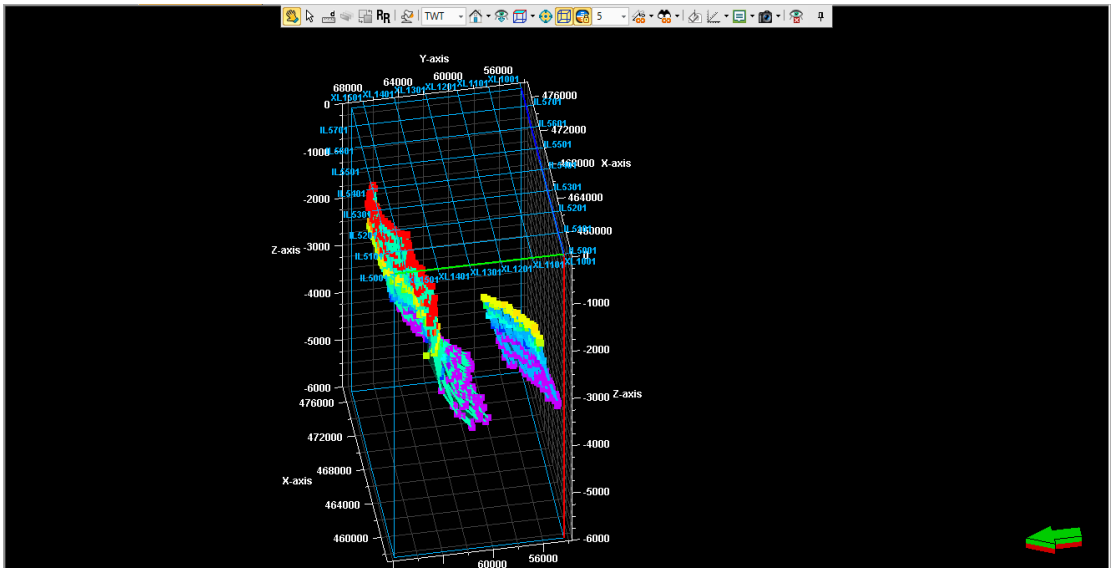


Figure 4 (b): 3D view of the interpreted fault sticks showing their position in the survey area

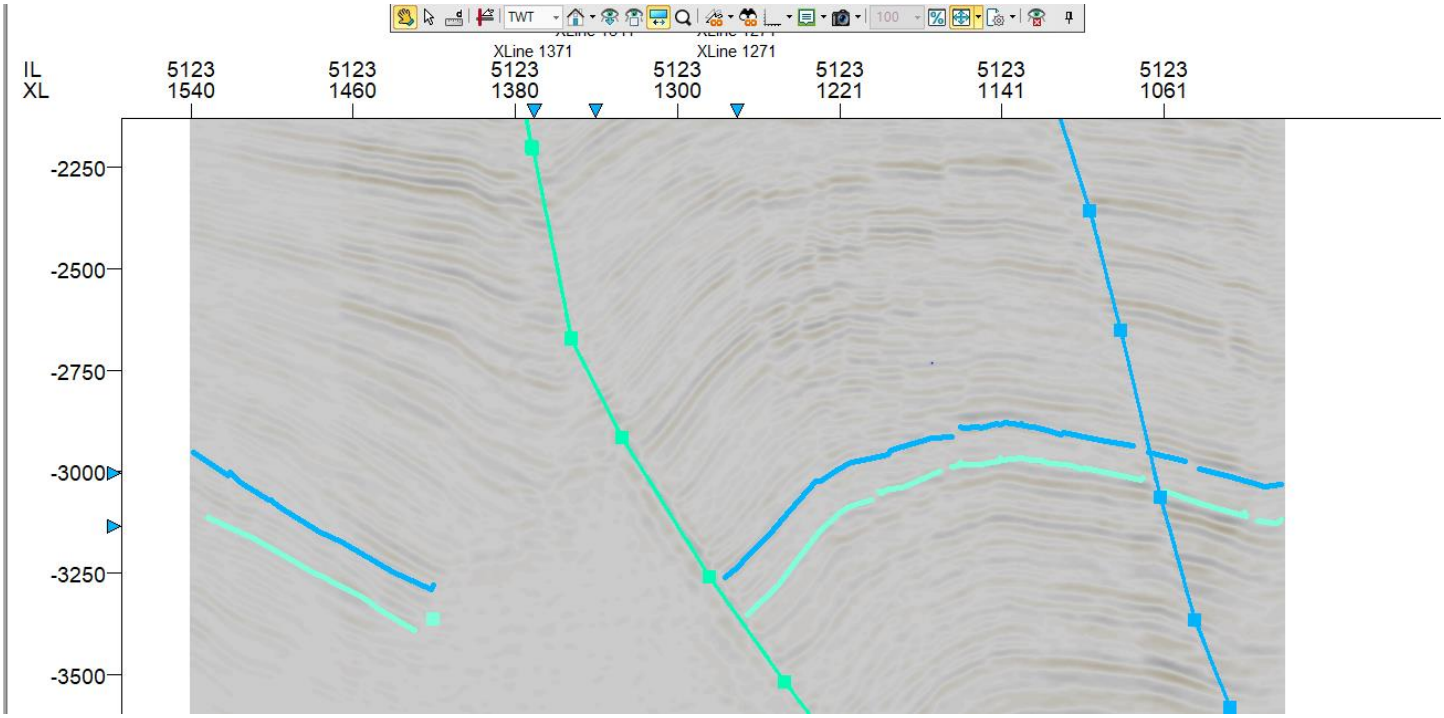


Fig: 5: Seismic Section (inline 5123) showing the faults and horizons mapped across the seismic volume.

To assess the sealing efficiency of fault zones for CO_2 storage, shale gouge ratio (SGR) was calculated using Vshale log data at fault throws of 0 m, 100 m, 200 m, and 300 m across a depth interval of 1000 – 2600 m. The SGR quantifies the proportion of shale (or clay-rich material)

smeared along fault planes, providing an indication of fault sealing potential. Higher SGR values, particularly those exceeding 0.5, are indicative of effective fault sealing, while values below this threshold suggest greater risk of CO_2 leakage. Table 2 presents the computed SGR fractions for each depth and throw scenario, highlighting zones of high seal integrity and identifying depths that may pose leakage risks due to insufficient clay content or excessive fault displacement.

Table 2 presents the computed SGR fractions for each depth and throw scenario, highlighting zones of high seal integrity and identifying depths that may pose leakage risks due to insufficient clay content or excessive fault displacement.

Table 2: Calculated depth and SGR fraction % at throws of 0, 100, 200, and 300.

		SGR/FRACTION %			
DEPT (m) /TVDSS	**Vshale**	**0**	**100**	**200**	**300**
1000	0.85	0.85			
1050	0.83	0.83			
1100	0.8	0.8	0.826667		
1150	0.81	0.81	0.8225		
1200	0.82	0.82	0.822	0.822	
1250	0.7	0.7	0.776667	0.801667	
1300	0.68	0.68	0.733333	0.762	0.784286
1350	0.65	0.65	0.676667	0.732	0.755714
1400	0.71	0.71	0.68	0.712	0.738571
1450	0.76	0.76	0.706667	0.7	0.732857
1500	0.8	0.8	0.756667	0.72	0.731429
1550	0.75	0.75	0.77	0.734	0.721429
1600	0.77	0.77	0.773333	0.758	0.731429
1650	0.79	0.79	0.77	0.774	0.747143
1700	0.83	0.83	0.796667	0.788	0.772857
1750	0.79	0.79	0.803333	0.786	0.784286
1800	0.72	0.72	0.78	0.78	0.778571
1850	0.71	0.71	0.74	0.768	0.765714
1900	0.7	0.7	0.71	0.75	0.758571
1950	0.71	0.71	0.706667	0.726	0.75
2000	0.72	0.72	0.71	0.712	0.74
2050	0.78	0.78	0.736667	0.724	0.732857
2100	0.8	0.8	0.766667	0.742	0.734286
2150	0.77	0.77	0.783333	0.756	0.741429
2300	0.75	0.75	0.773333	0.764	0.747143
2350	0.6	0.6	0.706667	0.74	0.732857
2400	0.04	0.04	0.463333	0.592	0.637143
2450	0.6	0.6	0.413333	0.552	0.62
2500	0.83	0.83	0.49	0.564	0.627143
2550	0.81	0.81	0.746667	0.576	0.628571
2600	0.83	0.83	0.823333	0.622	0.637143

Figure 6 presents a combined tabular and graphical analysis of fault seal potential using shale gouge ratio (SGR) derived from gamma-ray log-inferred Vshale values across depth intervals between 1000 m and 2600 m. The calculations were performed for fault throws of 0, 100, 200, and 300 meters using the formula:

$$SGR = \frac{\sum(Thickness \times Vshale)}{Throw}$$

The result shows:

1. SGR Trends Across Depth:
    - For throws of 100 – 300 m, SGR values remain consistently above the critical 0.5 threshold from 1000 m to approximately 2300 m, suggesting good sealing potential in this zone.
    - Below 2400 m, all SGR values drop significantly (e.g., SGR ≈ 0.04 – 0.49), indicating poor sealing capacity and a higher risk of fault-related CO_2 leakage.
2. Interpretation of the SGR Plot (Right Panel):
    - The plot displays SGR on the x-axis and depth (TVDSS) on the y-axis.
    - A vertical dashed line at SGR = 0.5 separates zones of expected sealing behavior (right side) from leaky fault conditions (left side).
    - Red (Throw 300 m), yellow (Throw 200 m), and green (Throw 100 m) lines show the progression of SGR with increasing throw.
    - The brown zone beneath 2300 m indicates depths where the SGR values for all throws fall below the sealing threshold —these are unsuitable for safe CO_2 storage.
3. Depth Range Classification:
    - 1000–2300 m: Faults exhibit SGR > 0.5, suitable for CO_2 storage. This zone includes the optimal injection interval of 1700 – 1900 m, where sealing is most effective across all throws.
    - >2300 m: Marked by low Vshale and low SGR values, indicating leaky fault conditions that are not suitable for CO_2 injection.

The analysis validates the presence of a robust sealing fault system from 1000 m to 2300 m, especially at the 100 – 300 m throw intervals. The highest integrity is observed between 1700 m - 1900 m, making this zone optimal for CO_2 injection. Below 2300 m, faults become increasingly transmissive due to declining SGR values, thus posing a leakage risk.

Interpreted seismic section across Well Y (left) correlated with the computed Shale Gouge Ratio (SGR) profile (right). The seismic profile shows fault geometry (red line), key reflectors (green horizon), and well penetration (yellow arrow), while the SGR plot illustrates sealing capacity across depths and fault throws (100 m, 200 m, 300 m). The SGR cutoff of 0.5 distinguishes sealing zones (left) from leaky faults (right), supporting site selection for CO_2 injection (figure 6a). The seismic profile presents an eastward-dipping fault, delineated in red, which transects the stratigraphic sequence and intersects the prospective reservoir interval. This geometry is indicative of a structurally controlled trap that may facilitate hydrocarbon or CO_2 entrapment.

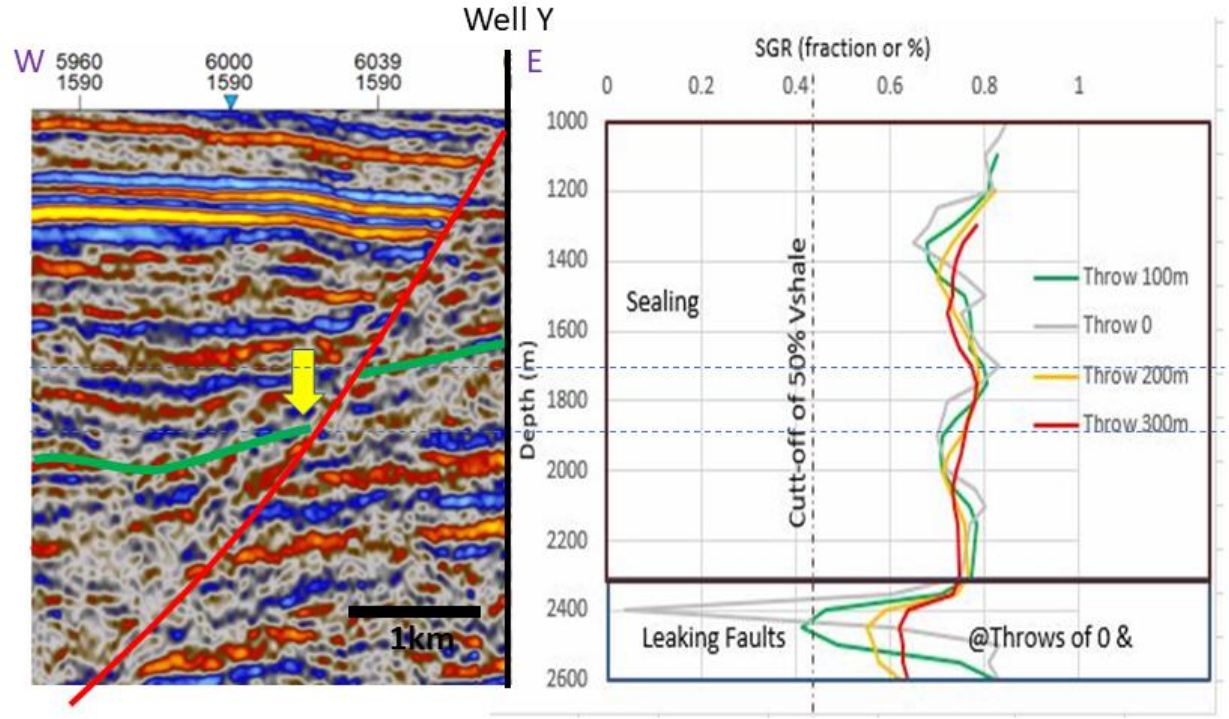


Fig. 6: showing an interpreted seismic well log data matched with the extracted SGR fraction.

The green horizon, representing a significant seismic reflector, likely corresponds to the top of the reservoir or a key caprock boundary. The position of Well Y, marked by a yellow arrow, reveals its trajectory through the fault zone at a depth interval of approximately 1700 – 1900 meters. Notably, reflector terminations against the fault surface suggest stratigraphic juxtaposition across the fault, a condition that may contribute to sealing if clay-rich units are juxtaposed with the reservoir.

The adjacent plot displays SGR values, calculated for fault throws of 0 m (grey), 100 m (green), 200 m (yellow), and 300 m (red), across a depth interval of 1000 to 2600 meters. The SGR metric ranging from 0 to 1, quantifies the volumetric contribution of shale along the fault plane and serves as a proxy for seal integrity. A vertical reference line at SGR = 0.5 is used to distinguish between fault zones likely to act as seals (SGR > 0.5) and those more prone to leakage (SGR < 0.5).

The results indicate that for all considered fault throws, SGR values remain consistently above the 0.5 threshold from 1000 m to approximately 2300 m, with maximum values observed between 1700 - 1900 m. This depth range coincides with the interval penetrated by Well Y and suggests a high likelihood of effective fault sealing due to elevated clay content and minimal fault reactivation risk. However, below 2300 m, a marked reduction in SGR is observed, particularly for throws ≥200 m where values fall below the sealing threshold. This trend signifies a transition to more

permeable fault conditions and reduced sealing capacity, rendering the deeper intervals less suitable for long-term CO_2 storage.

Conclusions

This study demonstrates the application of shale gouge ratio (SGR) analysis as a robust tool for evaluating fault seal integrity in CO_2 storage site assessments. Through the integration of Vshale logs, seismic interpretation and structural modeling, fault throws of 0 m - 300 m were analyzed to determine clay smear distribution and sealing potential across a 1000 – 2600 m depth interval. The findings indicate that the 1000 – 2300 m depth range possesses high SGR values (SGR > 0.5), confirming effective sealing conditions suitable for long-term CO_2 containment. The interval between 1700 m and 1900 m was identified as the most favorable for injection due to consistently elevated SGR values across all fault scenarios. Conversely, depths beyond 2300 m exhibited a sharp reduction in SGR indicating a transition to leaky fault regimes and reduced storage integrity. The seismic correlation at Well Y further validated these zones, linking favorable SGR trends with fault geometries and stratigraphic juxtaposition. Overall, the methodology and results support the use of SGR as a predictive metric for fault-controlled CO_2 storage security and provide a practical approach for early-stage site screening in the Niger Delta and similar geological settings

Recommendation

Future studies should extend the SGR-based fault seal assessment to other prospective fields within the Niger Delta Basin. A broader spatial analysis will help validate the reliability of identified sealing intervals and support regional CO_2 storage planning. While SGR provides information into clay content and sealing potential, integrating other fault seal evaluation methods such as shale smear factor (SSF), clay smear potential (CSP), and fault permeability modeling can improve confidence in seal integrity assessments.

To complement static SGR analysis, numerical simulations of CO_2 injection and migration should be conducted to evaluate caprock performance under pressure buildup and stress changes over time

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