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Integrated Evaluation of Aging Well as CO_2 Storage Reservoirs in the South Sumatera Basin

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Abstract

This study assesses the CO_2 storage potential of an aging well in the South Sumatra Basin through the interpretation of conventional well log data, including gamma ray (GR), bulk density (RHOB), neutron porosity (NPHI), deep and shallow resistivity logs (LLD and MSFL), and caliper measurements. The evaluated interval, ranging from 1200 to 1800 meters, is subdivided into an upper formation (1200-1500 m) and a lower formation (1500-1800 m). The upper formation exhibits low gamma ray values but minimal separation between porosity and resistivity logs, suggesting low porosity and permeability, characteristics indicative of a potential cap rock. In contrast, the lower formation reveals distinct separation in both porosity and resistivity responses below 1650 meters, indicative of a porous sandstone with favorable reservoir properties. Petrophysical analysis yields an average effective porosity of 14.4% and an irreducible water saturation of 6.4%. Volumetric calculations estimate a theoretical CO_2 storage capacity of approximately 1.21 million metric tons per square kilometer. These findings demonstrate the feasibility of repurposing aging wells for CO_2 sequestration and emphasize the utility of well log analysis in early-stage site screening, particularly in data limited sedimentary basins.

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Introduction

The global urgency to mitigate anthropogenic carbon dioxide (CO_2) emissions has driven rapid advancements in Carbon Capture and Storage (CCS) technologies. Among the various strategies, geological storage of CO_2 particularly in deep saline aquifers and depleted hydrocarbon reservoirs has emerged as one of the most promising and scalable approaches for achieving long- term emission reductions [1,2]. The effectiveness of such storage projects, however, is highly dependent on the accurate identification of subsurface formations that can function both as high-capacity reservoirs and as reliable sealing units to ensure containment over geological timescales [3, 4].

Southeast Asia, and Indonesia in particular, possesses considerable geological potential for CO_2 storage owing to its widespread sedimentary basins, which have developed through complex tectonic and depositional processes [5]. Within this regional context, the South Sumatra Basin stands out due to its mature petroleum systems, thick sedimentary successions, and a range of lithologies capable of acting as both reservoir and seal units [6,7]. Despite a well-established history of hydrocarbon exploration and production, the CO_2 storage potential of the South Sumatra Basin remains relatively underexplored.

This study aims to perform a comprehensive petrophysical evaluation of an aging well located within the South Sumatra Basin to assess its feasibility for geological CO_2 storage. The analysis is centered on the interpretation of conventional wireline log data to characterize two key stratigraphic intervals: a lower unit with potential as a CO_2 storage reservoir, and an overlying formation that may serve as a cap rock. Emphasis is placed on the interpretation of gamma ray, density, neutron porosity, and resistivity logs, which are essential for delineating reservoir quality zones and identifying effective sealing intervals [8,9].

Although the evaluation is based on a single aging well, the findings provide valuable preliminary insight into the local reservoir–seal system and establish a foundation for broader CO_2 storage assessments across the basin. Moreover, this study demonstrates the utility of log- based interpretation as a cost-effective and technically robust approach for early-stage site screening, particularly in data-constrained sedimentary basins such as South Sumatra [10].

Methodology

This study adopts a conventional petrophysical approach based on well log interpretation to assess the geological suitability of an aging well in the South Sumatra Basin for CO_2 storage.

The methodology is organized into five sequential stages: (1) acquisition and quality control of well log data, (2) stratigraphic zonation and lithological interpretation, (3) estimation of effective porosity, (4) calculation of irreducible water saturation, and (5) volumetric estimation of theoretical CO_2 storage capacity. Each stage incorporates standard interpretation techniques and mathematical models widely applied in subsurface reservoir evaluation, ensuring a systematic and reproducible workflow for preliminary site screening [11,12].

Well Log Acquisition

The first step involves the acquisition and validation of well log data, which form the basis for all subsequent petrophysical interpretations. The dataset comprises conventional open hole logs obtained from a vertical aging well that intersects the stratigraphic interval between 1200 and 1800 meters. The logs utilized include gamma ray (GR), bulk density (RHOB), neutron porosity (NPHI), deep resistivity (LLD), shallow resistivity (MSFL), and caliper measurements.

Each log serves a distinct purpose in subsurface characterization. Gamma ray logs are employed for lithological discrimination, particularly in identifying shale or clay-rich intervals. Density and neutron porosity logs are jointly analyzed to estimate porosity and infer lithological composition, while resistivity logs provide insights into formation fluid content and mobility [8,9]. Caliper logs are used to assess borehole integrity and to identify zones affected by washouts or enlargement, which may compromise log reliability. Prior to analysis, all log data were standardized, cleaned, and cross-checked to ensure consistency and accuracy throughout the petrophysical workflow [13].

Stratigraphic Zonation and Lithological Identification

The second stage involves the subdivision of the logged interval into two principal stratigraphic units referred to as the upper and lower formations based on changes in log character and petrophysical responses. The primary objective is to differentiate between intervals with potential reservoir quality and those that may function as sealing formations. This classification is guided by the integration of gamma ray, porosity, and resistivity log responses.

The upper formation, extending from 1200 to 1500 meters, is marked by relatively low gamma ray readings but exhibits minimal separation between the bulk density (RHOB) and neutron porosity (NPHI) curves, as well as between deep (LLD) and shallow (MSFL) resistivity logs. These characteristics suggest a compact lithology with low porosity and limited fluid mobility, indicative of a non-reservoir facies that may serve as a cap rock [8].

In contrast, the lower formation, particularly from around 1650 meters downward, displays clear separation between RHOB and NPHI logs, as well as between LLD and MSFL resistivity curves. This log behavior is typical of porous sandstones potentially hydrocarbon-depleted and signifies the onset of a reservoir-quality interval suitable for CO_2 storage [14, 6].

Effective Porosity Estimation

Effective porosity (ϕ_e) represents the proportion of interconnected pore space within a rock that is capable of storing and transmitting movable fluids, such as CO_2. It is a key parameter in reservoir evaluation and is commonly estimated from density log data using the following standard equation [3, 8]:

$$\phi e = \frac{(\rho ma - \rho b)}{(\rho ma - \rho f)} \qquad \textit{equation 1.}$$

Where :

ϕ_e : *effective porosity (fraction)*

ρ_{ma} : *matrix density (typically 2.65 g/cm³ for sandstone)*

ρ_b : *bulk density (from RHOB log)*

ρ_f : *fluid density (typically 1.0 g/cm³ for brine)*

This method assumes a homogeneous rock matrix and a uniformly fluid filled pore system. The calculation is applied to the lower formation (1500-1800 m), with particular emphasis on the interval beginning at 1650 meters, where distinct porosity log responses are observed. The effective porosity values obtained from this approach serve as critical input parameters for subsequent calculations of irreducible water saturation and theoretical CO_2 storage capacity [12].

Irreducible Water Saturation (Swi) Estimation

Irreducible water saturation (Swi) denotes the fraction of pore volume occupied by immobile water that is electrochemically bound to the surfaces of mineral grains and cannot be displaced by injected CO_2. This parameter is essential in estimating the volume of pore space available for CO_2 storage. Swi is calculated using Archie's water saturation equation [3]:

$$S_w = \left(\left(\frac{a}{\phi_e{}^m} \right) x \left(\frac{R_w}{R_t} \right) \right)^{\left(\frac{1}{n}\right)} \qquad \textit{equation 2.}$$

Where :
Sw = water saturation
a = tortuosity factor (typically 1)
ϕe = effective porosity
m = cementation exponent (commonly 2 for sandstone)
n = saturation exponent (typically 2) Rw = formation water resistivity (Ω·m)
Rt = true formation resistivity (from LLD log, Ω·m)

Irreducible water saturation (Swi) is estimated by identifying the minimum stable water saturation (Sw) values within the reservoir interval [8]. These values typically occur in zones where water saturation remains relatively constant, regardless of variations in formation resistivity. Such behavior is a strong indicator of immobile water that is electrochemically bound to the pore surfaces and not free to move or be displaced by injected fluids such as CO_2. In practical terms, these intervals are interpreted as representing irreducible conditions, where capillary forces dominate and fluid mobility is negligible. The estimation of Swi is a critical component in calculating effective storage capacity because it directly influences the volume of pore space available for CO_2 injection. Only the fraction of pore volume not occupied by irreducible water mathematically expressed as (1 − Swi) can be considered accessible for CO_2 storage [15]. Overlooking this factor could lead to significant overestimation of storage potential. Therefore, incorporating accurate Swi values not only improves the reliability of volumetric assessments but also enhances the predictability of CO_2 behavior in the reservoir, especially during early-stage screening in data-limited settings [16].

Volumetric Estimation of CO2 Storage Capacity

The theoretical mass of CO_2 that can be stored in the reservoir is estimated using a volumetric approach that incorporates petrophysical parameters derived from well log analysis. The calculation considers only the interconnected pore space available after accounting for irreducible water saturation, using the following equation:

$$M_{CO2} = A \times h \times \phi_e \times (1 - S_{wi}) \times \rho_{CO2} \times E_f \qquad \text{equation 3.}$$

Where:

MCO2 = theoretical mass of CO_2 that can be stored (metric tons),

A = area of the reservoir (1 km² = 1×106 m2) h = net reservoir thickness (in meters)

ϕe = 0.144 (interpreted effective porosity) Swi = irreducible water saturation (fraction)

ρCO2 = CO_2 density under reservoir conditions (~600 kg/m³),

Ef = storage efficiency factor (typically 0.3 for saline aquifers, per [17])

This volumetric approach is based on the assumption that the reservoir is laterally continuous and lithologically homogeneous, with a well-defined thickness and spatial extent [18]. Such assumptions are commonly applied during early-stage site evaluations, where detailed subsurface data may still be limited. To ensure reliability and minimize the risk of overestimation, conservative values are used for key parameters such as CO_2 density approximated at 600 kg/m³ under reservoir conditions and the storage efficiency factor, typically set at 0.3 for saline aquifers, based on empirical studies and international guidelines [13].

Although this method simplifies many complex geological and engineering factors such as capillary pressure effects, reservoir compartmentalization, and injectivity variation it nonetheless provides a valuable first-order estimate of CO_2 storage capacity. The outcome serves as a baseline for evaluating the feasibility of CO_2 injection and offers a preliminary measure of the reservoir's potential to contribute to long-term carbon sequestration efforts [14, 19]. Moreover, this approach lays the groundwork for more detailed analyses in subsequent phases, including dynamic reservoir modeling, geomechanical assessment, and risk-based site characterization [10,11]. As such, it is a critical step in the broader process of selecting and developing secure and effective geological storage sites.

Result

The petrophysical interpretation of the aging well reveals distinct variations in reservoir quality and sealing potential across the stratigraphic column. The log analysis confirms the presence of two main formations: an upper compact formation (1200-1500 m) and a lower formation (1500- 1800 m) with reservoir potential shown in Figure 1. The effective reservoir zone begins at approximately 1650 m, based on clear separations between neutron and density porosity logs

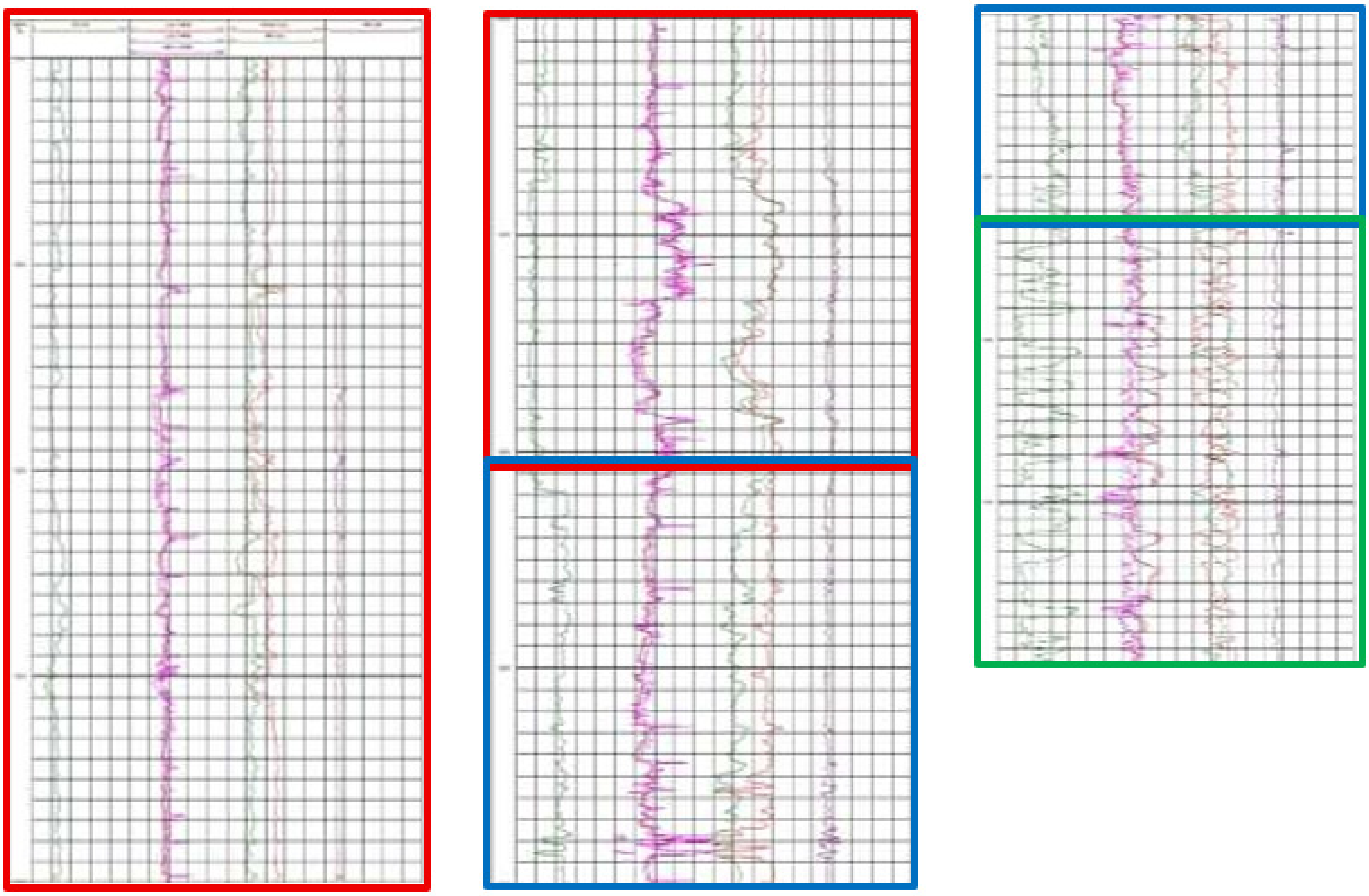

Figure 1: From the left to right; Gamma Ray log, resistivity log (LLD, LLS, MSFL) and, RHOB log X NPHI log and PEF log for 1200-1800 with the red box is the upper formation, the blue box is the lower formation and the green box is the lower formation and the reservoir zone

(NPHI-RHOB), as well as between deep and shallow resistivity logs (LLD-MSFL), which are classical indicators of increased porosity and fluid mobility.

Above the reservoir, the 1200-to-1400-meter depth interval exhibits consistently low gamma ray responses, low porosity values, and minimal RHOB NPHI separation, all of which are indicative of a shale dominated lithology. These properties align with the expected characteristics of an effective geological seal, suggesting that this cap rock unit could provide sufficient vertical containment to prevent CO_2 migration and ensure long term storage security.

Petrophysical Properties

Within the delineated reservoir interval (1650-1800 m), the average effective porosity, as calculated from the density (RHOB) log, is approximately 14.4% ($\phi_e = 0.144$). This value indicates a substantial volume of interconnected pore space capable of accommodating injected CO_2. Furthermore, water saturation values derived from Archie's equation reveal an average irreducible water saturation (Swi) of 6.4% (0.064), suggesting that over 93% of the pore volume remains available for CO_2 occupancy.

These petrophysical properties fall within the expected range for storage grade sandstones and reinforce the suitability of the interval as a potential CO_2 storage zone. Moderate gamma ray responses indicate low shale content, while the clear separation between neutron porosity (NPHI) and bulk density (RHOB) curves supports the interpretation of a clean and porous sandstone lithology. In addition, the contrast observed between shallow (MSFL) and deep (LLD) resistivity logs further implies the historical presence of movable formation fluids either hydrocarbons or brine indicating that the pore system is now accessible for CO_2 injection.

The relationship between effective porosity and water saturation is depicted in Figure 2, which illustrates an inverse correlation between PHIE and Sw across the 1600-1800 m interval. This pattern provides additional confirmation of the reservoir's favorable petrophysical characteristics for CO_2 storage applications.

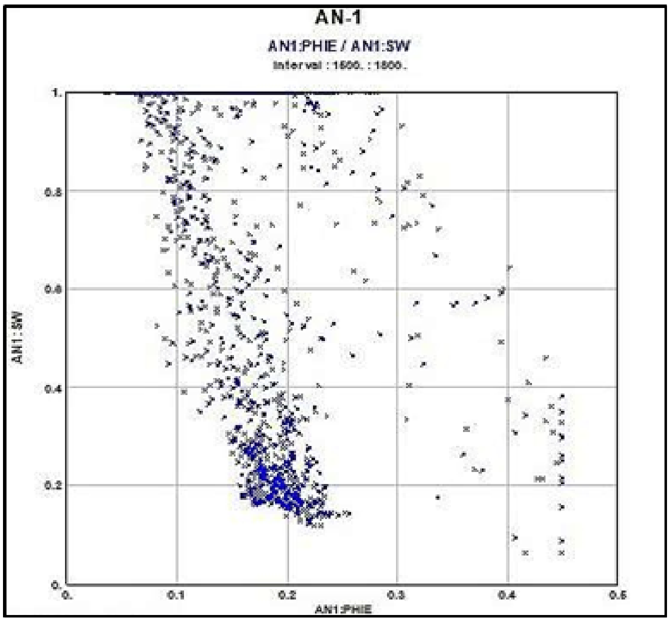

Figure 2: Cross plot of effective porosity (PHIE) vs. water saturation (Sw) for the AN-1 well, interval 1600-1800 m, showing an inverse relationship indicative of clean, wellconnected pore systems favorable for CO_2 storage.

Reservoir Thickness

The reservoir thickness used for volumetric estimation was defined from the top of the reservoir quality log responses at 1650 m to the total depth at 1800 m, resulting in a net reservoir thickness of 150 meters. This interval is interpreted as laterally continuous and lithologically homogeneous for the purposes of preliminary evaluation. As shown in Figure 3, the effective porosity (PHIE) values within this interval are relatively consistent and remain above 10% in multiple zones, while the corresponding water saturation (Sw) is low, supporting the interpretation of a clean and interconnected sandstone reservoir. Additionally, gamma ray readings indicate a moderate to low shale content, reinforcing the classification of this interval as a viable CO_2 storage target.

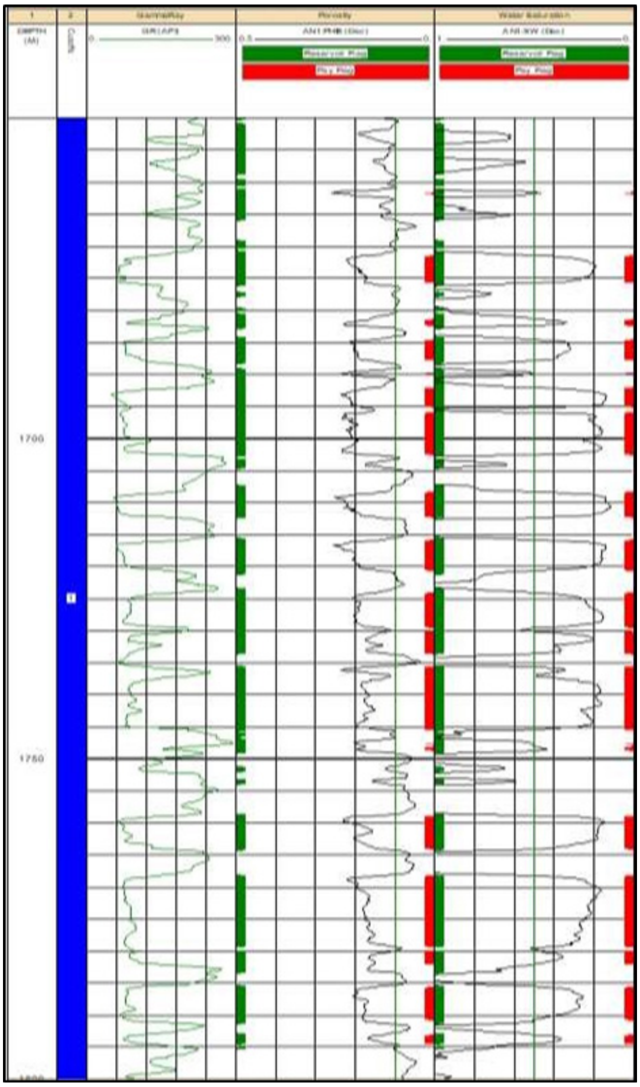

Figure 3: GR log, PHIE and Sw at 1650-1800 Meter as Reservoir Zone

CO_2 Storage Capacity

Based on the petrophysical parameters obtained namely effective porosity, irreducible water saturation, net reservoir thickness, and standard assumptions for CO_2 density and storage efficiency the theoretical storage capacity for CO_2 within the 1650-1800 m reservoir interval was calculated. By assuming an area of one square kilometer, a net thickness of 150 meters, an effective porosity of 14.4%, and an irreducible water saturation of 6.4%, combined with a CO_2 density of approximately 600 kg/m^3 and a conservative storage efficiency factor of 0.3, the estimated storage capacity is approximately 1.22 million metric tons per square kilometer.

This estimation assumes ideal injection conditions and a homogeneous reservoir, without accounting for possible geological heterogeneities or structural complexities. Nevertheless, it serves as a reliable first order approximation and a practical foundation for guiding further site characterization and simulation efforts.

Discussion

The findings of this study underscore the significant potential of repurposing aging wells as viable candidates for geological CO_2 storage in the South Sumatra Basin. Through comprehensive petrophysical interpretation, a clear vertical contrast is observed between a compact, low porosity upper interval interpreted as a sealing unit and an underlying porous sandstone with favorable reservoir characteristics. This distinct reservoir–seal arrangement plays a vital role in ensuring both the effectiveness and safety of CO_2 storage operations, as it supports key trapping mechanisms including structural confinement and residual saturation. The presence of such a configuration is essential for long-term containment, offering reassurance that injected CO_2 can remain securely stored within the subsurface over geological timescales [14]. These results not only validate the geological suitability of the study area, but also reinforce the broader potential of re-evaluating mature wells as part of future carbon storage strategies.

Reservoir Suitability

The lower formation, particularly the interval between 1650 and 1800 meters, demonstrates clear petrophysical signatures characteristic of a brine-saturated or previously hydrocarbon- bearing sandstone reservoir. This formation has fluctuated gamma ray values that are not stable, which the lower values have range from 60-120 API, and the higher values have range from 200- 280 API. The fluctuated values of gamma ray possibly caused by the numerous interbed between sandstone and shale lithology. This stratigraphic pattern makes the tool more sensitive, hence the graphics fluctuate. Compared to the upper formation that is more stable, it's so clear that the lower formation has more fluctuations and this condition causes speculation that the lower formation has higher gamma ray values and is more suitable for seal. However, it is important for looking at other well log data to validate our interpretation. The separation from NPHI and RHOB log indicate more porous formation and is suitable for accommodating CO_2. Therefore, the high gamma ray values in lower zone do not indicate formation rich in radioactive minerals such as shale, but is indicating to interbeds lithology that increase tool's sensitivity.

An average effective porosity of 14.4% indicates the presence of well-connected pore spaces that are capable of accommodating CO_2 in its supercritical phase. This porosity falls within the globally accepted range for CO_2 storage in sandstone reservoirs, which typically spans between 10% and 20% [13,16].

Moreover, the irreducible water saturation (Swi), calculated at 6.4%, suggests that only a small portion of the pore space is occupied by bound water, leaving approximately 93.6% available for CO_2 injection. Such low Swi values are favorable, as they improve storage efficiency and minimize the risk of early CO_2 breakthrough or injectivity decline [15]. Log-based indicators specifically the separation observed between shallow and deep resistivity logs (MSFL and LLD), as well as between neutron and density porosity logs (NPHI and RHOB) reinforce the interpretation of good fluid mobility and suggest the potential for favorable permeability, despite the absence of direct permeability measurements [9].

The volumetric estimate of approximately 1.22 million metric tons of CO_2 per square

kilometer highlights the substantial storage potential within this single well. When extrapolated across other similar intervals or neighboring legacy wells, this capacity could translate into a meaningful carbon sink for mitigating industrial CO_2 emissions in South Sumatra and its surrounding regions. These findings not only demonstrate the technical feasibility of CO_2 storage in mature fields, but also emphasize the strategic value of leveraging existing well infrastructure for scalable, region-wide climate solutions [18].

Seal Integrity

The upper formation, spanning depths from 1200 to 1500 meters, does not exhibit characteristics typically associated with reservoir quality, despite its relatively low gamma ray readings. Gamma ray value in this zone ranged between 60-120 API, indicating shaly sandstone lithology. Although the lower formation looks like has higher gamma ray value, but this condition is the result from fluctuating values that is caused by numerous interbeds that is dominating in lower formation. Other well log data in upper formation also validates this interpretation. The absence of separation between neutron porosity (NPHI) and bulk density (RHOB), as well as between shallow (MSFL) and deep (LLD) resistivity logs, indicates a dense and compact lithology with minimal pore connectivity. Although its precise lithological composition remains uncertain whether shale or another fine-grained facies its log responses align with those of an effective sealing unit capable of acting as a cap rock to prevent upward CO_2 migration.

Cap rock integrity plays a fundamental role in ensuring long-term CO_2 containment. While direct measurements such as pressure data or capillary entry pressure are not available in this study, the log-derived interpretation provides reasonable evidence of a competent lithostatic seal [21]. The considerable burial depth and compact nature of this formation further strengthen the case for its effectiveness in minimizing leakage risks. In the context of CO_2 storage, the presence of such a sealing interval directly above a porous reservoir is a favorable configuration, reinforcing the geological security of the proposed storage site.

Implication and Limitations

The integration of conventional well log data in this study has demonstrated its value as a cost- effective and informative approach for identifying potential CO_2 storage intervals, particularly in settings where access to core samples, pressure data, or seismic surveys is limited or unavailable [11]. This method is especially relevant during early-stage site screening, where rapid yet reliable assessments of reservoir quality and seal integrity are essential for guiding further technical and economic evaluations [10].

Despite the encouraging results, several limitations should be acknowledged to contextualize the findings. The analysis is based solely on a single well, which constrains the ability to assess lateral heterogeneity, reservoir continuity, and regional scalability. Furthermore, the estimation of storage capacity relies on the assumption of uniform reservoir properties and does not incorporate the effects of structural complexity, stratigraphic variability, or dynamic flow behavior all of which could influence CO_2 injectivity and long-term containment [18, 22].

While the use of conservative, literature-based values for CO_2 density and storage efficiency helps reduce the risk of overestimation, these parameters still introduce a degree of uncertainty that would benefit from calibration using site-specific data [19]. To enhance the robustness of future assessments, additional efforts should include the acquisition of 3D seismic data, pressure– temperature logging, capillary entry pressure measurements, and dynamic reservoir simulations. Reentering aging wells for wellbore integrity testing and pilot-scale CO_2 injection could also provide critical operational insights and further validate the suitability of such sites for long-term geological storage [8].

Conclusion

This study provides a preliminary evaluation of an aging well in the South Sumatra Basin for geological CO_2 storage using conventional petrophysical analysis. The lower formation (1650– 1800 m) demonstrates promising storage characteristics, with an effective porosity of 14.4% and low irreducible water saturation (6.4%), yielding an estimated storage capacity of 1.22 million metric tons/km² [13,16]. The overlying compact lithology (1200–1500 m) exhibits seal-like properties, supporting the potential for long-term CO_2 containment [21].

Although based on a single well, the results highlight the viability of conventional log data for early-stage screening in data-limited regions [11]. Limitations include the absence of seismic or dynamic data, suggesting the need for follow-up studies incorporating 3D seismic, well tests, and reservoir simulation [19]. Nonetheless, the findings support the strategic repurposing of legacy wells for scalable CO_2 storage applications in mature basins [23,24].

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