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Geomechanical Integrity Assessment in Field X of the Telisa Formation Caprock for CO_2 Storage in the Central Sumatra Basin

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ABSTRACT

Evaluating caprock integrity is essential to ensure the long-term security of geological CO_2 storage. This study investigates the elastic and geomechanical characteristics of the Telisa Formation in the Central Sumatra Basin as a potential caprock for Carbon Capture and Storage (CCS) using well log data from four wells (C-1, H-1, P-1, and T-1). Elastic properties, including Young's Modulus (1–15 GPa) and Poisson's Ratio (0.30–0.50), were calculated to derive the Brittleness Index, while Unconfined Compressive Strength (35–65 MPa) was estimated to evaluate rock strength. The results indicate that the Telisa Formation is predominantly shale-dominated with high gamma ray values and low porosity, consistent with typical caprock characteristics. Acoustic Impedance, Young's Modulus, and UCS generally increase with depth, indicating progressive compaction and increasing rock stiffness. Crossplot analysis reveals positive correlations among Acoustic Impedance, Young's Modulus, Brittleness Index, and UCS, whereas Poisson's Ratio shows an inverse relationship with stiffness-related parameters. Although localized brittle intervals are identified, particularly in Well P-1, the formation is generally dominated by ductile to less brittle behavior. Overall, the Telisa Formation demonstrates favorable elastic and geomechanical characteristics for long-term CO_2 containment. However, localized brittle zones and potential structural discontinuities should be carefully considered to minimize leakage risks during CO_2 injection operations.

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1. INTRODUCTION

In evaluating the potential for geological carbon dioxide (CO_2) storage, the assessment typically starts with an analysis of the storage system, particularly the caprock. In Carbon Capture and Storage (CCS), the caprock serves as the primary barrier that prevents the vertical migration of CO_2 from the reservoir to overlying formations or even to the surface, ensuring that it remains securely trapped over the long-term. Although several CCS projects worldwide have demonstrated safe and stable CO_2 storage, the security of storage depends on the strength of the caprock and the presence of surrounding geological structures (Rahman et al., 2022). Therefore, caprock characterization is crucial in every CCS project to minimize the risk of CO_2 leakage.

In general, a caprock must have low porosity and permeability, seal thickness at least 10 m, and exhibit elastic or ductile behavior to withstand pressure increases during CO_2 injection

(Chadwick, 2008; Chevalier et al., 2010; Ramírez et al., 2010). An increase in pressure within the caprock can reduce the normal stress on a fault surface and potentially trigger the formation of new fractures or the reactivation of existing faults (Olden, et al., 2012; Raza, et al., 2015). Variations in petrophysical, acoustic, elastic, and geomechanics properties may create local heterogeneities that weaken the caprock (Rahman et al., 2022). In addition, the presence of geological structures such as faults influences the integrity of the caprock in preventing fluid migration. Faults can be barriers or fluid migration zones. Pressure buildup due to CO_2 injection may increase permeability through slip reactivation because the shear stress on the fault exceeds the shear strength of the rock, thereby enhancing permeability and increasing the risk of CO_2 leakage (Raza, et al., 2015)

The Telisa Formation in the Central Sumatra Basin is recognized as a regional caprock dominated by shale lithology (Marpaung, Katz, & Amlan, 2010). Despite its established role as a sealing formation, investigations focusing on its elastic and geomechanical characteristics within the framework of CCS are still limited. Accordingly, this study seeks to assess the rock's elastic behavior, quantified through Young's Modulus (E) and Poisson's Ratio (PR), which are further utilized to calculate the Brittleness Index (BI). The Brittleness Index serves as a key parameter in caprock assessment, reflecting the rock's susceptibility to brittle failure. Caprock with a high BI values are more susceptible to forming fractures when experiencing increased pressure, which may potentially increase permeability significantly (Perez & Marfurt, 2014; Handoyo, et al., 2025). Moreover, Unconfined Compressive Strength (UCS) is commonly applied to evaluate the rock's mechanical strength in resisting in-situ stresses (Widita & Sapiie, 2021). The integration of these parameters is intended to deliver a more comprehensive evaluation of the Telisa Formation's capability as a caprock for secure and long-term CO_2 injection.

2. METHODS

2.1 Geological Setting

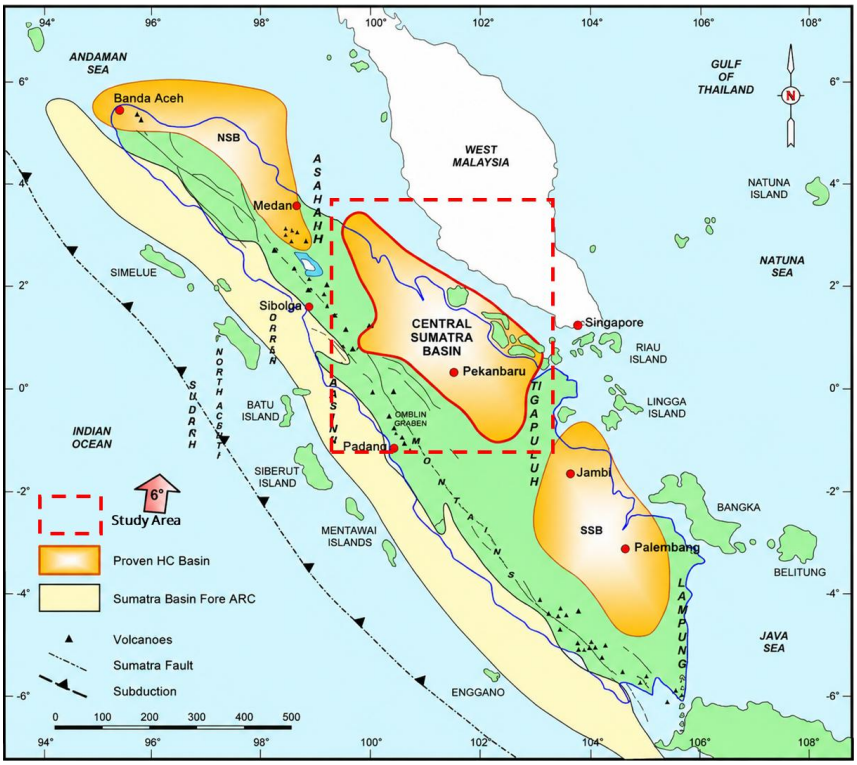


Figure 1. Study Area (Modified from Heidrick & Aulia, 1993)

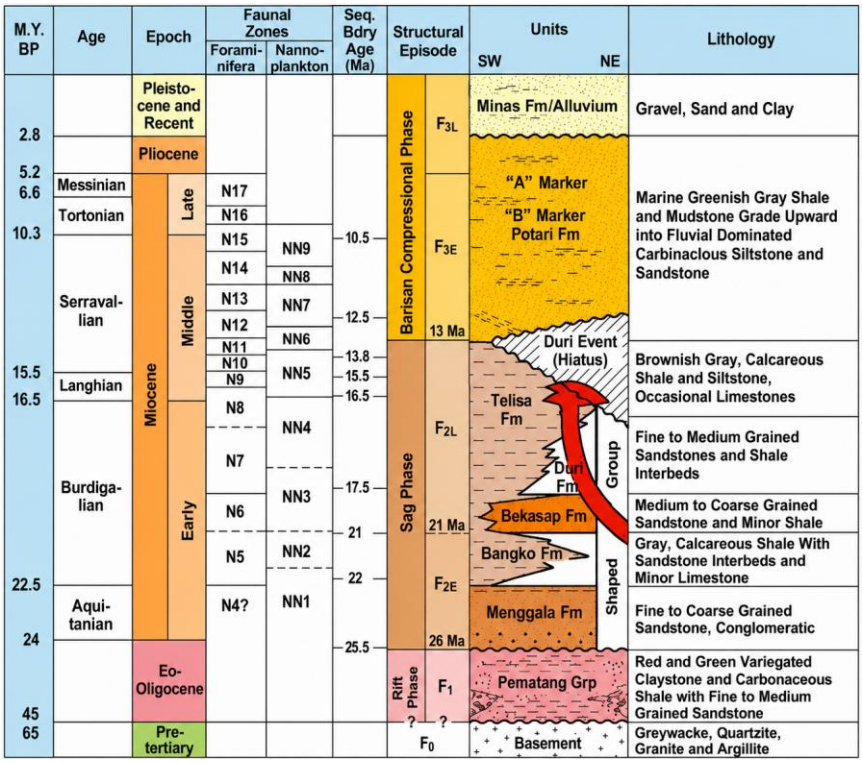


Figure 2. Regional stratigraphy of the Central Sumatra Basin (Heidrick & Aulia, 1993)

The Telisa Formation is located within the Central Sumatra Basin, one of the major sedimentary basins in Indonesia. Tectonically, the basin developed as a back-arc basin associated with the subduction of the Indo-Australian Plate beneath the Eurasian Plate. The basin contains thick sedimentary successions consisting of reservoir and sealing formations that are considered prospective for geological CO_2 storage (Heidrick & Aulia, 1993).

Stratigraphically, the Telisa Formation is predominantly composed of shale and siltstone lithologies with low permeability characteristics, making it a potential regional caprock. Although thin sandstone interbeds occur locally within the formation, they do not significantly alter its dominant sealing behavior (Heidrick & Aulia, 1993). Underlying the Telisa Formation are several sandstone-dominated units, including the Bangko, Bekasap, Menggala, and Pematang Formations, which are considered potential storage reservoirs for CO_2 injection. The vertical configuration between porous sandstone reservoirs and the overlying regional shale seal provides a favorable geological framework for long-term CO_2 containment.

2.2 Data Availability

The data used in this study consists of four wells, namely Well C-1, Well H-1, Well P-1, and Well T-1. The available data includes gamma ray (GR), sonic (DT), bulk density (RHOB), and predicted shear wave velocity (Vs) logs for each well, with Vs calculated using the Castagna equation.

Table 1. Data Availability

Well	GR	DT	RHOB	Vs
C-1	✓	✓	✓	Predicted
H-1	✓	✓	✓	Predicted
P-1	✓	✓	✓	Predicted
T-1	✓	✓	✓	Predicted

2.3 Rock Elastic Calculation

Geomechanical characterization is essential for evaluating rock deformation behavior, mechanical stability, and sealing integrity within geological CO_2 storage systems. In this study,

several elastic and geomechanical parameters were derived, including Young's Modulus (E), Poisson's Ratio (PR), Brittleness Index (BI), and Unconfined Compressive Strength (UCS). These parameters were used to evaluate the stiffness, deformational behavior, and failure tendency of the Telisa Formation as a potential caprock.

Rock elastic properties are generally classified into static and dynamic elastic properties. Static elastic properties are obtained directly from laboratory measurements on core samples under applied stress conditions, whereas dynamic elastic properties are calculated indirectly from elastic wave velocities derived from well logs, particularly compressional-wave velocity (Vp), shear-wave velocity (Vs), and density logs. Dynamic elastic properties are commonly higher than static values because they are measured under small-strain elastic conditions. Young's Modulus (E) represents the ratio between stress and elastic strain and describes the stiffness of a rock under deformation. In geomechanical studies, E is an important parameter because it indicates the resistance of a rock to elastic deformation. Rocks with high Young's Modulus values tend to be stiffer and mechanically brittle, whereas rocks with lower values generally exhibit more ductile behavior. Elastic modulus is influenced by several geological factors, including mineral composition, porosity, grain size, compaction, and fluid content (Perez & Marfurt, 2014).

Since shear-wave velocity (Vs) data were not available in this study, Vs was estimated from compressional-wave velocity (Vp) using the Castagna mudrock relationship shown in Equation (1). This empirical relationship is widely applied in siliciclastic formations dominated by shale and sandstone lithologies, which are characteristic of the Telisa Formation.

$$\text{Vs} = 0.826 \times \text{Vp} - 1.172 \tag{1}$$

where Vp and Vs are in km/s. The Castagna equation was selected because it was developed for clastic sedimentary rocks and has been widely used for shale-dominated intervals where direct Vs measurements are unavailable.

After estimating Vs, Young's Modulus was calculated using Equation (2).

$$E = \rho V_s^2 \frac{(3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} \tag{2}$$

where:

- E= Young's Modulus
- ρ= bulk density
- V_p= compressional-wave velocity
- V_s= shear-wave velocity

This equation relates elastic wave propagation to rock stiffness under elastic deformation conditions. Higher E values indicate rocks with greater rigidity and lower deformability, which are commonly associated with brittle mechanical behavior. Poisson's Ratio (PR) describes the ratio between lateral strain and axial strain when a material is subjected to stress. This parameter reflects the deformational response of rocks under compressive loading. Higher PR values generally indicate ductile behavior, whereas lower PR values are associated with brittle deformation.

Poisson's ratio (PR) describes the relationship between axial deformation and lateral deformation in a material under stress. Specifically, when a compressive force is applied along one axis, the material deforms by expanding in the transverse directions, a response referred to as the Poisson effect. Elevated PR values are typically associated with ductile deformation, while lower PR values correspond to more brittle responses (Ma et al., 2016). The PR can be calculated from Vp and Vs data using the Equation (3).

$$\text{PR} = 0.5 \times \frac{(V_p^2) - 2(V_s^2)}{(V_p^2 - V_s^2)} \tag{3}$$

In geomechanical analysis, PR is important for evaluating the tendency of rocks to undergo plastic deformation or fracture propagation during stress changes induced by CO_2 injection.

Brittleness Index (BI) is a geomechanical parameter used to estimate the tendency of rocks to behave in a brittle or ductile manner. Brittle rocks tend to fracture more easily under stress, while ductile rocks deform plastically without significant fracture development. In CCS applications, BI is particularly important because elevated pore pressure during CO_2 injection may reduce effective stress and potentially induce caprock failure. In this study, BI was calculated using the elastic-based method proposed by Grieser, Bill, and Bray (2007), which integrates normalized Young's Modulus and Poisson's Ratio values. This approach assumes that brittle rocks are characterized by high Young's Modulus and low Poisson's Ratio values.

$$\text{BI}= \frac{1}{2}\left[\frac{E-E_{min}}{E_{max}-E_{min}} + \frac{PR-PR_{max}}{PR_{min}-PR_{max}}\right] \quad (4)$$

where:

- E_{max} and E_{min} are the maximum and minimum Young's Modulus values
- PR_{max} and PR_{min} are the maximum and minimum Poisson's Ratio values

2.4 Rock Strength Estimation

Rock strength is the ability of rock to withstand the stress conditions surrounding it. Rock strength properties include Unconfined Compressive Strength (UCS), tensile strength, and rock friction angle. In this case, UCS is widely used to determine rock strength and can be obtained from the triaxial compressive strength test conducted on core sample. The value obtained represents those from a continuous profile, whereas for constant profile, the calculation is performed using the Altindag Equation (2012) (Equation (5)). A higher UCS value indicates a stronger resistance of the rock to applied compressive stress. For shale, UCS generally falls within the range of 70 to 120 MPa

$$\text{UCS} = 12.746\ \text{Vp}^{1.194} \quad (5)$$

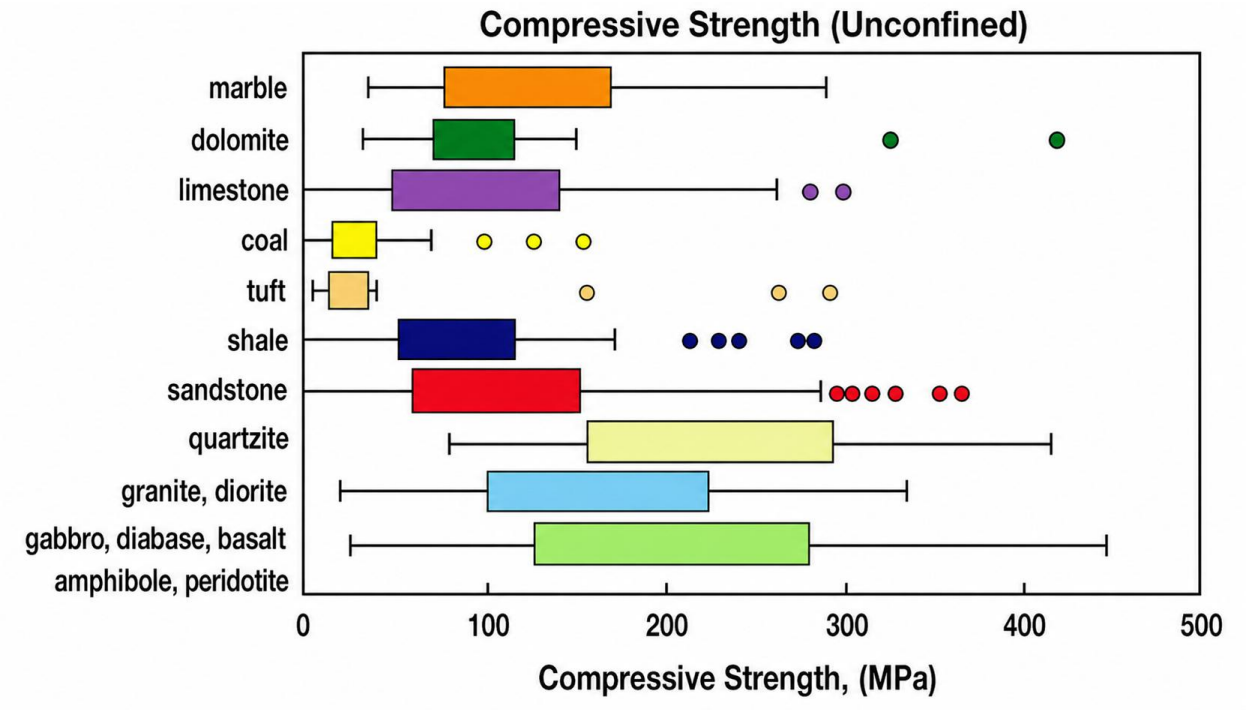


Figure 3. Range of UCS values in rocks (Zoback, 2007)

3. RESULT AND DISCUSSION

3.1 Well Log Analysis

The analyzed interval of the Telisa Formation ranges from approximately 1290 to 1380 m depth and is characterized predominantly by shale lithology. This interpretation is supported by relatively high Gamma Ray (GR) values ranging from approximately 100 to 160 API, indicating high clay mineral content throughout most intervals. The calculated volume shale values also consistently indicate shale-dominated characteristics. In several upper intervals, particularly above approximately 1350 to 1370 m, lower GR responses suggest the presence of thin sandstone interbeds; however, these intervals are limited and do not significantly alter the dominant shale character of the formation.

The RHOB log shows relatively stable density values with minor variations, indicating a relatively compacted formation. In addition, the DT log generally decreases with increasing depth, especially below approximately 1330 m, indicating increasing compressional-wave velocity associated with progressive burial compaction. The combined RHOB and DT responses produce relatively low porosity values throughout the analyzed interval without significant porosity enhancement, which is consistent with the characteristics of low-permeability shale acting as a sealing formation.

Acoustic Impedance (AI) generally increases with depth due to increasing density and wave velocity associated with compaction. This increase is particularly evident below approximately 1330 m. The increase in AI is accompanied by increasing Young's Modulus (E), which ranges approximately from 1 to 15 GPa. Higher E values indicate stiffer rock behavior and lower elastic deformability. Mechanically, intervals with elevated E values tend to exhibit more brittle characteristics because the rock is less capable of accommodating deformation plastically. In contrast, Poisson's Ratio (PR) ranges between approximately 0.30 and 0.50 and tends to increase in intervals where E values are relatively low. This inverse relationship indicates that intervals with high PR and low E are mechanically more ductile, whereas intervals characterized by higher E and relatively lower PR exhibit a greater tendency toward brittle deformation.

The relatively ductile behavior observed in several intervals is associated with the high clay mineral content of the Telisa Formation. Clay-rich shale commonly exhibits ductile deformation because of its fine-grained texture and platy mineral structure, which allow deformation through particle reorientation and sliding mechanisms. Furthermore, the presence of bound water within clay minerals may reduce rock stiffness and enhance plastic deformation behavior. Consequently, shale-dominated intervals with high PR and low E are interpreted as mechanically ductile and less susceptible to brittle fracture development.

The vertical variation of Brittleness Index (BI) further supports this mechanical differentiation. Higher BI values are predominantly observed below approximately 1330 m and correspond to higher AI and E values, indicating stiffer and mechanically brittle intervals. Conversely, lower BI values are associated with lower AI and E values in shallower intervals, reflecting more ductile mechanical characteristics.

Overall, the Telisa Formation exhibits increasing stiffness and brittleness with depth, particularly within the interval of approximately 1330 to 1380 m, due to progressive compaction and increasing elastic wave velocity. Nevertheless, the formation remains dominated by shale lithology with relatively low porosity and ductile characteristics in several intervals, supporting its potential role as an effective regional caprock for geological CO_2 storage.

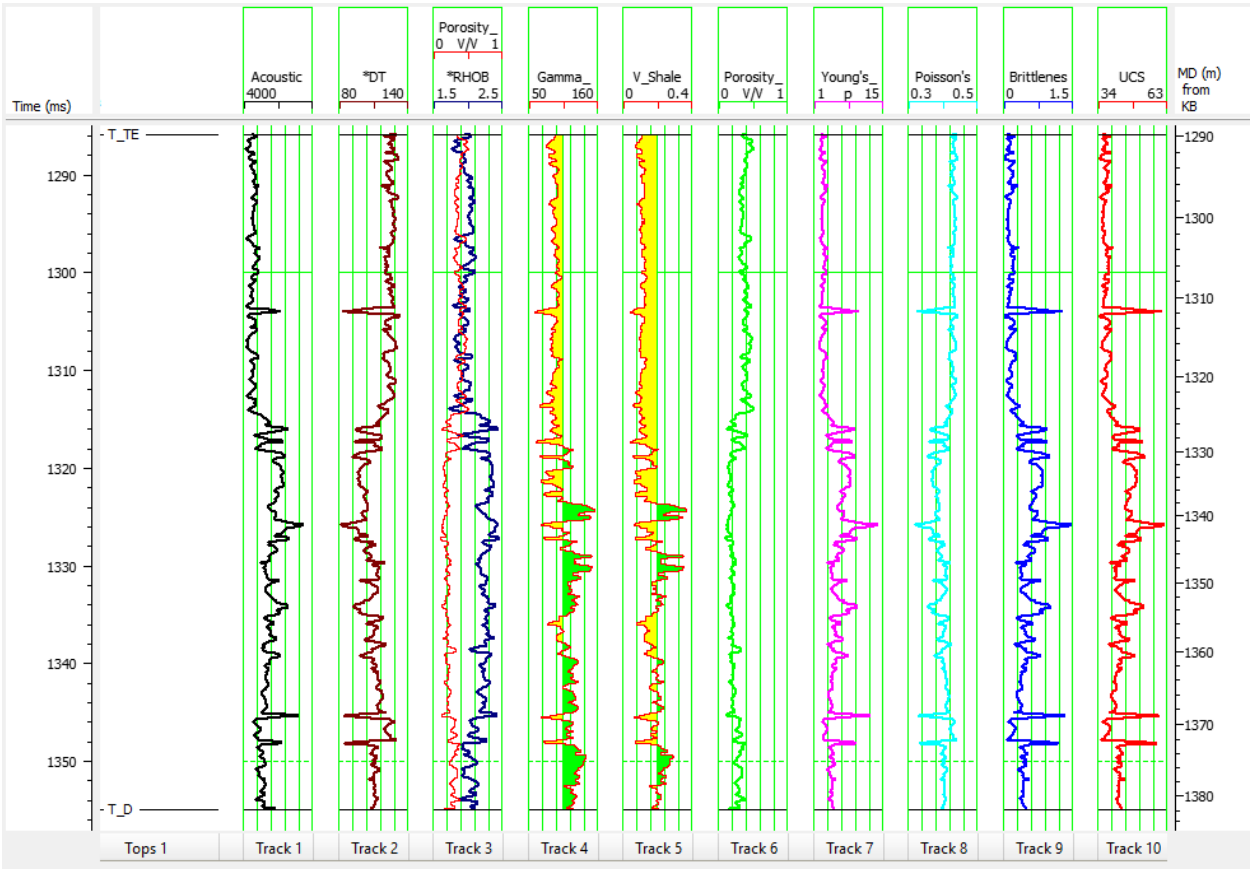


Figure 4. Well Log Analysis of Well C1.

3.2 Brittleness Index

Brittleness Index (BI) is a quantitative parameter used to evaluate the mechanical behavior of caprock formations, although its estimation may vary significantly depending on the applied method and geological setting. Since no universally accepted definition of brittleness exists, BI is commonly used as a practical indicator for assessing rock mechanical response under stress conditions (Altindag, 2012). In this study, BI was estimated using elastic-derived geomechanical parameters obtained from well-log data. The brittleness classification follows the empirical classification proposed by Perez and Marfurt (2014) for the Barnett Shale, where BI values of 0–0.16 are classified as ductile, 0.16–0.32 as less ductile, 0.32–0.48 as less brittle, and values greater than 0.48 as brittle. The classification was originally developed from empirical partitioning of brittleness data within the Barnett Shale dataset rather than from universal geomechanical thresholds. Therefore, these cutoff values should be interpreted as relative brittleness indicators when applied to different geological formations such as the Telisa Formation. Due to the absence of formation-specific brittleness classification for the Telisa Formation, the Perez and Marfurt classification is adopted in this study as a comparative elastic-based reference framework.

Based on this classification, the calculated BI values indicate that the Telisa Formation is generally dominated by ductile to less ductile behavior, with several localized intervals classified as less brittle. The BI distribution is relatively consistent across wells C-1, H-1, P-1, and T-1, although Well P-1 exhibits a tendency toward relatively higher BI values compared to the other wells. This suggests the presence of mechanically stiffer intervals that may have relatively higher susceptibility to localized fracturing. In contrast, wells C-1, H-1, and T-1 display a more evenly distributed pattern dominated by ductile to less ductile behavior. The generally high Gamma Ray values ranging from approximately 100 to 160 API observed within the formation indicate shale-dominated lithology, which commonly corresponds to relatively ductile mechanical characteristics.

The crossplot between Poisson's Ratio (PR) and Young's Modulus (E) demonstrates a very strong negative correlation (R = 0.984), indicating an inverse elastic relationship between rock stiffness and lateral deformation capacity. R = 0.984 Intervals characterized by relatively higher

Young's Modulus and lower Poisson's Ratio tend to cluster within mechanically stiffer domains, whereas intervals with lower Young's Modulus and higher Poisson's Ratio are associated with more ductile behavior. This relationship suggests that increasing elastic stiffness is generally accompanied by reduced deformability within the shale-dominated intervals.

A similar positive relationship is observed in the crossplot between Young's Modulus (E) and Acoustic Impedance (AI), which exhibits a very strong positive correlation (R = 0.978). R = 0.978 Increasing AI values are generally associated with increasing elastic stiffness because Acoustic Impedance is influenced by seismic velocity and rock density, which are closely related to elastic rock properties (Mavko et al., 2009). Since Acoustic Impedance is controlled by seismic velocity and rock density, this relationship reflects increasing elastic stiffening and rock compaction within the observed dataset.

The crossplot between Brittleness Index (BI) and Acoustic Impedance (AI) also demonstrates a strong positive correlation (R = 0.960), R = 0.960 indicating that intervals with relatively higher BI values generally correspond to higher AI values. This trend suggests that mechanically stiffer intervals tend to exhibit greater acoustic impedance and reduced deformability. Conversely, the crossplot between Poisson's Ratio (PR) and Acoustic Impedance (AI) exhibits a strong negative correlation (R = 0.947), R = 0.947 indicating that increasing AI values are generally associated with decreasing PR values. Intervals characterized by low PR and high AI commonly correspond to relatively higher BI values, highlighting the influence of elastic stiffening and compaction on rock rigidity.

However, the strong correlations observed between BI, AI, E, and PR should be interpreted carefully because these parameters share partial dependence on elastic properties derived from seismic velocity and density. Therefore, the observed relationships may partly reflect elastic parameter dependency in addition to physical rock behavior. Furthermore, shale elastic response may also be influenced by mineralogical composition, clay content, quartz distribution, diagenetic variations, pore structure, and lithological heterogeneity, which are not fully represented by elastic-derived parameters alone (Perez & Marfurt, 2014; Jin et al., 2014)

Overall, the shale-dominated Telisa Formation caprock is characterized by relatively low Brittleness Index (BI), low to moderate Young's Modulus (E), moderate to high Poisson's Ratio (PR), and generally moderate Acoustic Impedance (AI), indicating dominantly ductile to less ductile mechanical behavior. These characteristics are considered favorable for caprock integrity because ductile shale intervals are generally less susceptible to fracture propagation and permeability enhancement during subsurface stress changes associated with depth and CO_2 injection (Yin et al., 2018). Nevertheless, several localized intervals exhibiting relatively higher BI, elevated AI, higher E, and lower PR values indicate mechanically stiffer zones that may respond differently under injection-induced stress conditions. Therefore, further analyses such as in-situ stress evaluation, fracture gradient analysis, fault stability assessment, mineralogical characterization, and laboratory geomechanical testing are recommended to comprehensively evaluate long-term caprock integrity within the Telisa Formation (Song et al., 2023).

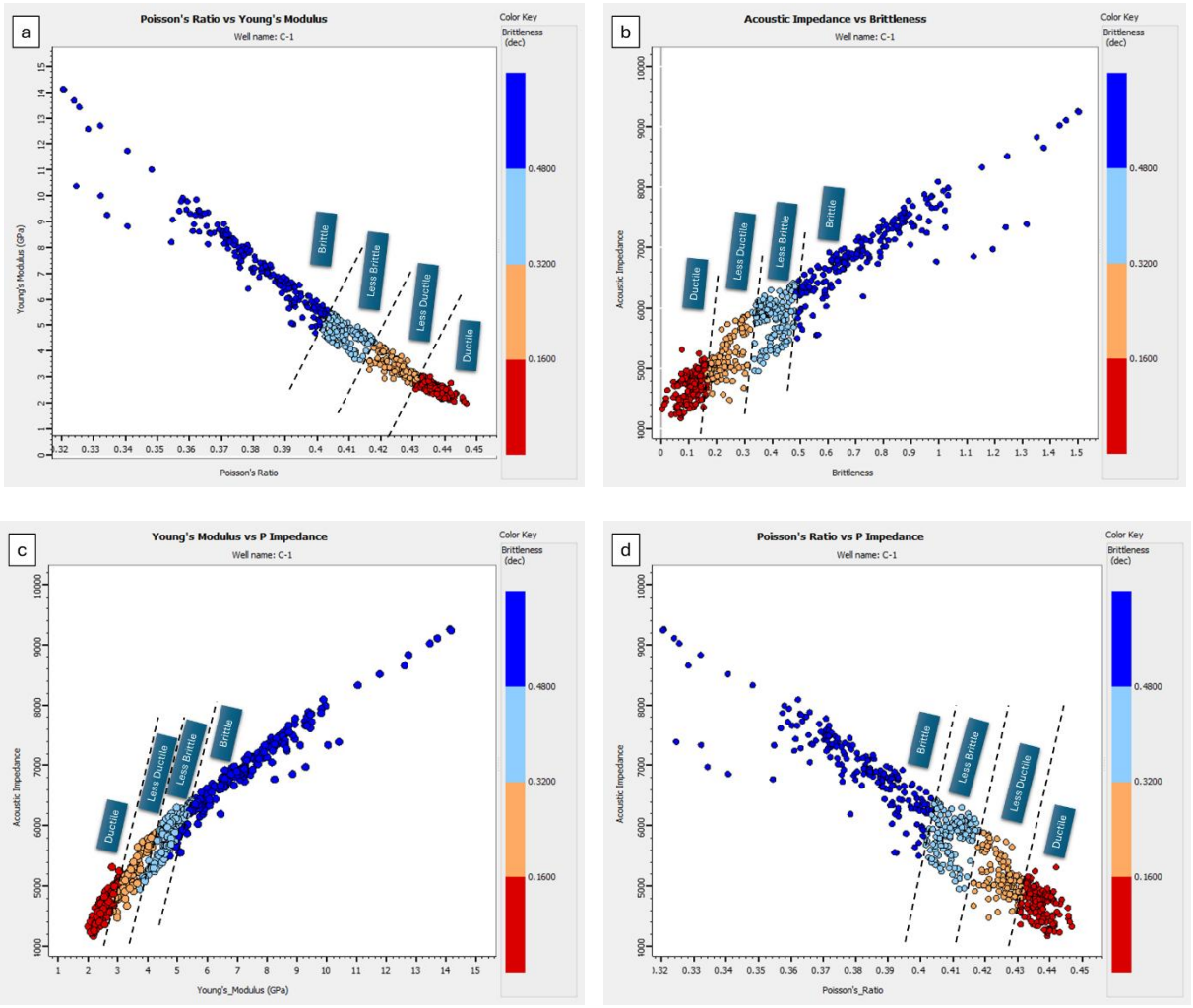


Figure 5. Cross-plot of PR versus E color-coded with BI (a), Cross-plot of BI versus AI color-coded with BI (b), Cross-plot of E versus AI color-coded with BI (c), Cross-plot of PR versus AI color-coded with BI (d)

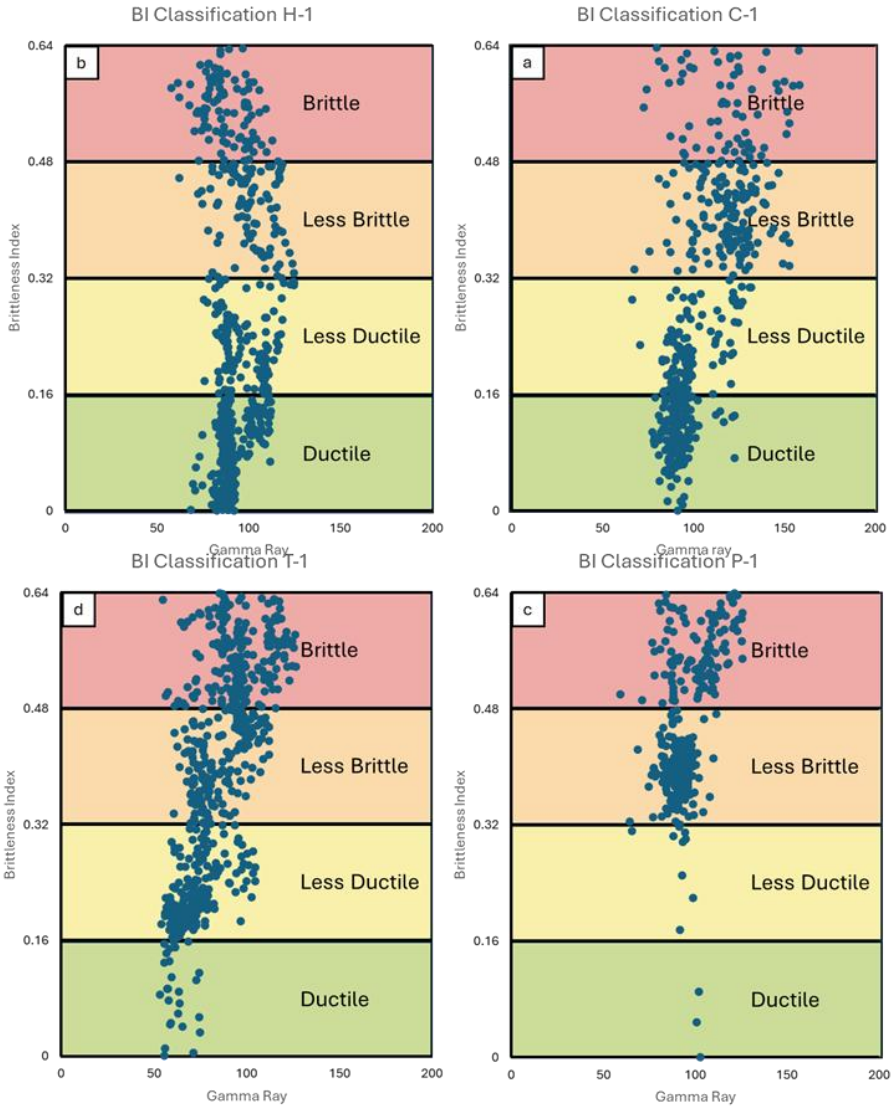


Figure 6. Brittleness Index Classification in wells C-1, H-1, P-1, and T-1 using the classification of Perez and Marfurt (2014).

3.3 Unconfined Compressive Strength

Rock strength in this study is represented by the Unconfined Compressive Strength (UCS) value as a parameter describing the rock's ability to withstand applied stress. The crossplot results between UCS and Acoustic Impedance (AI) show a positive correlation, where an increase in AI is followed by an increase in UCS. This indicates that more compact rocks with higher density and wave velocity generally exhibit stronger compressive strength.

However, UCS values within certain intervals do not fully align with the rock strength classification proposed by Zoback (2007). These discrepancies may reflect differences in depositional environment, mineral composition, degree of compaction, and cementation. Such geological variability directly influences elastic response and mechanical strength. Despite these differences, the UCS distribution pattern within this interval remains consistent with the Brittleness Index (BI) trend. Intervals characterized by high UCS values are associated with higher BI values. This correlation suggests that mechanically stronger rocks also tend to exhibit more brittle behavior. Therefore, UCS, AI, and BI collectively provide complementary insights into the geomechanical characteristics of the formation and its caprock integrity.

Overall, the shale-dominated Telisa Formation caprock is characterized by relatively low to moderate Unconfined Compressive Strength (UCS) values, moderate Acoustic Impedance (AI), and generally low Brittleness Index (BI), indicating dominantly ductile to less ductile mechanical

behavior. These characteristics suggest that the caprock possesses relatively good deformation capacity and may be less susceptible to fracture propagation and permeability enhancement under subsurface stress conditions. Nevertheless, several localized intervals exhibiting relatively higher UCS, elevated AI, and increased BI values indicate mechanically stiffer zones that may respond differently to stress changes during subsurface activities such as CO_2 injection.

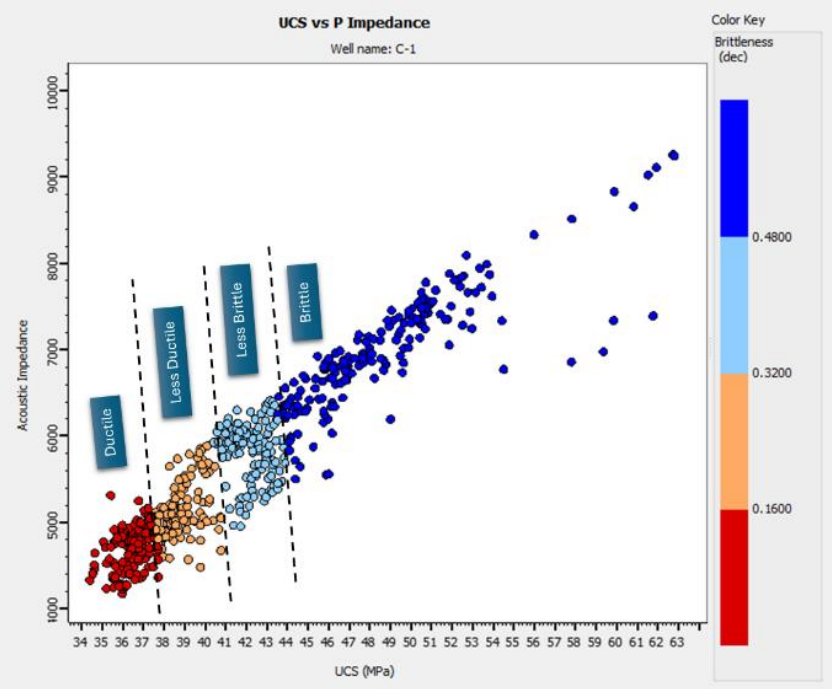


Figure 7. UCS in well C-1

4. CONCLUSION

The Telisa Formation is predominantly characterized by shale lithology with low porosity and favorable mechanical properties for caprock applications. Young's Modulus ranges from 1–15 GPa, Poisson's Ratio ranges from 0.32–0.45, and UCS ranges from 34–63 MPa, indicating moderate to high rock stiffness and mechanical strength. Brittleness Index analysis suggests that the formation is largely dominated by ductile to less ductile behavior, although localized brittle intervals are present, particularly in Well P-1.

These results indicate that the Telisa Formation generally possesses favorable characteristics for long-term CO_2 containment through its tendency to accommodate stress by ductile deformation. Nevertheless, localized brittle intervals may still represent potential fracture-prone zones under elevated injection pressure conditions, highlighting the presence of mechanical heterogeneity within the formation.

Further integration with seismic structural interpretation, in-situ stress evaluation, fault stability analysis, and laboratory geomechanical testing is recommended to improve the assessment of long-term caprock integrity and CO_2 containment security within the Telisa Formation.

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