



A GEOMECHANICAL APPROACH TO WELLBORE STABILITY IN THE SOUTH SUMATRA BASIN

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ABSTRACT: Wellbore instability continues to pose a major operational challenge in the South Sumatra Basin, largely due to the limited availability of integrated field-scale geomechanical modeling. This study develops a comprehensive one-dimensional (1D) geomechanical model and performs wellbore stability analysis for deviated wells in the S Field to support pre-drilling design and establish safe mud-weight requirements across varying well inclinations. Multiple data sources from nearby wells were integrated, including wireline logs, formation integrity and leak-off test results, pressure measurements, rock mechanical data, drilling reports, gamma-ray logs, and mud-logging records. Petrophysical interpretation, shear-wave velocity estimation, and application of the Mogi–Coulomb failure criterion were employed to define safe mud-weight windows for key stratigraphic intervals. Results indicate that in well S-9, pore pressure within the PRE-TERTIARY formation reflects an estimated pressure drop of approximately 1600 psi. The formation exhibits an unconfined compressive strength of about 3708 psi and a friction angle of 24.6°. Based on Mogi–Coulomb failure analysis, the safe mud-weight window for well S-9 ranges between 9.4 and 12.1 ppg. Model calibration using caliper data and drilling records confirmed predicted breakout behavior, improving confidence in stability predictions. Mechanical Earth Models developed for wells S-3 and S-4 were extended to wells S-8 and S-9, and sensitivity analyses were conducted to refine mud-weight recommendations and reduce shear-failure risk. The analysis further indicates that maintaining well inclination below 30° is essential for stable drilling. These findings provide practical geomechanical guidance for optimizing drilling performance in the South Sumatra Basin.

Keywords: Geomechanics, Geomechanics Modeling, Wellbore Stability, Drilling, Mud Weight

1. INTRODUCTION

The development of oil and gas resources requires careful evaluation of several key geological and engineering factors, with wellbore stability being one of the most critical considerations [1]. Field S is located along the northeastern margin of the Central Palembang Sub-basin within the larger South Sumatra Basin of Indonesia. Geographically, it is positioned in South Sumatra Province, northwest of Palembang City. The South Sumatra Basin itself is a Tertiary back-arc system that spans roughly 500 km in length and about 300 km in width, with its principal axis oriented parallel to the length of Sumatra Island. Toward the northwest, the basin transitions into the Central Sumatra Basin, with which it shares a broadly comparable stratigraphic framework. Drilling operations in Field S began in 1994, when the first exploratory well penetrated the granitic pre-tertiary basement (PRT) and resulted in a gas discovery [2]. A map illustrating the Field S location is presented in Fig.1.

The South Sumatra Basin (SSB) consists of several structural sub-basins in which tertiary sedimentary

units rest upon eroded metamorphic basement and older igneous rocks. It is regarded as one of Indonesia's most productive onshore Tertiary back-arc basins and is characterized by half-graben structures filled with carbonate and clastic deposits. The basin's development is interpreted to be associated with an extensional pull-apart setting influenced by northwest–southeast–trending dextral strike-slip faulting [3].

Structurally, the South Sumatra Basin is separated into four major sub-basins: Jambi, North Palembang, Central Palembang, and South Palembang. Geologically, it forms part of the Sumatra back-arc province, which developed in response to the interaction between the Eurasian (Sunda Shield) and Indo-Australian plates [4]. Basin subsidence commenced in the Late Eocene as a result of extensional tectonics along the southwestern margin of Sunda Land [5,6]. This rifting phase initiated the accumulation of Early Tertiary syn-rift sediments, followed by a subsequent marine transgression from the Late Oligocene to Early Miocene that led to the deposition of the Gumai, Talang Akar, and Baturaja Formations.

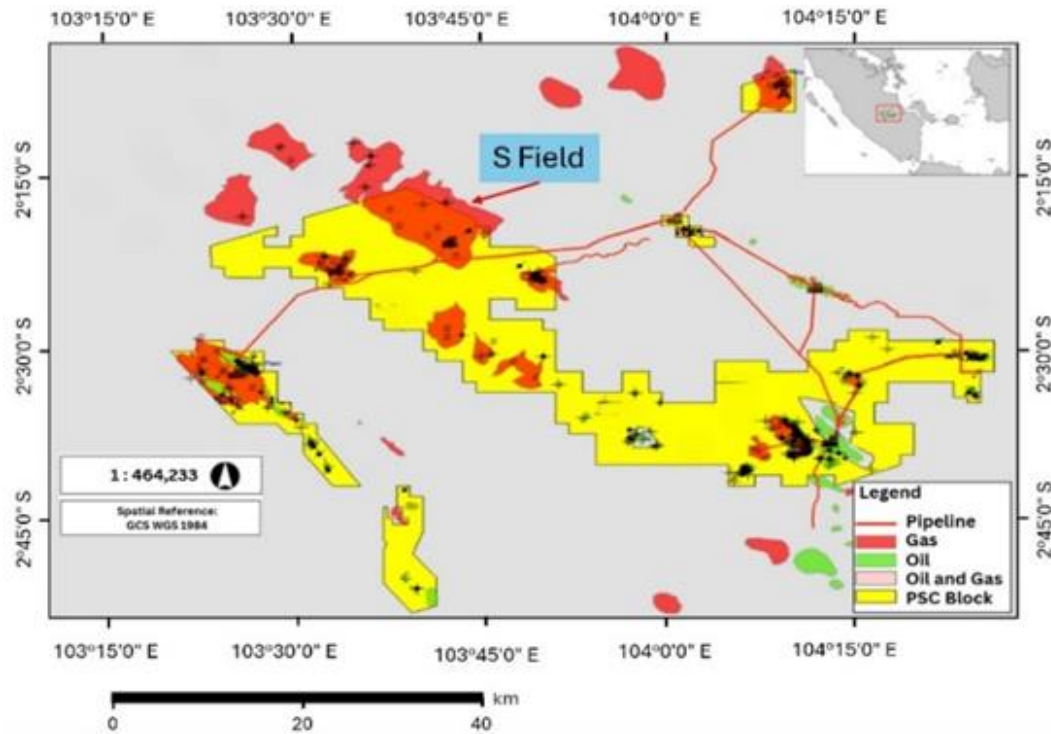


Fig 1. Location Map of S Field

Fractal-geometry approaches are widely used to examine intricate geological features in geophysics, geological engineering, and mineral exploration. Methods such as class-area analysis, class-number evaluation, and power-spectrum techniques are commonly applied to interpret branching geological patterns and to differentiate geochemical and mineralogical zones.

During the Paleogene, regional extensional stresses led to an enlargement of the sedimentary depocenter and resulted in the development of two major normal faults along the basin margin [7]. Physical sandbox modeling has been used to replicate the pull-apart basin configuration, and these experiments demonstrated how the basin geometry evolved above a dextral strike-slip fault system and a stable basement framework [8]. The principal structural elements associated with the Paleogene evolution of the SSB are illustrated in Figure 2, and the overall stratigraphic succession of the basin is shown in Figure 3. Wellbore stability represents a critical factor governing drilling safety, operational efficiency, and hydrocarbon productivity. Geomechanical analysis is routinely applied to anticipate the response of the surrounding rock mass to pore pressure and in-situ stresses during drilling operations. In geologically complex settings such as the South Sumatra Basin, the Mechanical Earth Model (MEM) serves as a robust analytical tool for evaluating subsurface pressure regimes and determining suitable mud-weight parameters,

thereby reducing the likelihood of wellbore failure.

Field S, the second-largest producing area in the block, has eight drilled wells but continues to encounter significant geomechanical problems. Well S-8, in particular, required three sidetracks as a result of recurrent instability [2]. Wellbore stability is recognized as essential for safe and economical drilling operations [8], as instability can lead to substantial wellbore damage and increased operational costs [9]. In this study, a one-dimensional (1D) geomechanical model is developed for the South Sumatra Basin by integrating geological and geophysical datasets, including wireline logs, drilling information, and rock-mechanics evaluations.

The method employs sensitivity analysis together with the the Mogi–Coulomb–based failure analysis used to constrain the safe mud-weight range constrained by formation pressure and rock strength. In addition, the calibrated mechanical models from wells S-3 and S-4 are transferred to wells S-8 and S-9, providing a practical means of addressing data limitations and enhancing drilling safety and operational efficiency in the area.

The main objective of this study is to determine optimal geomechanical parameters to prevent shear failure and wellbore collapse in geologically complex formations. Wellbore instability is a major contributor to increased drilling costs and delays, making geomechanical analysis essential.

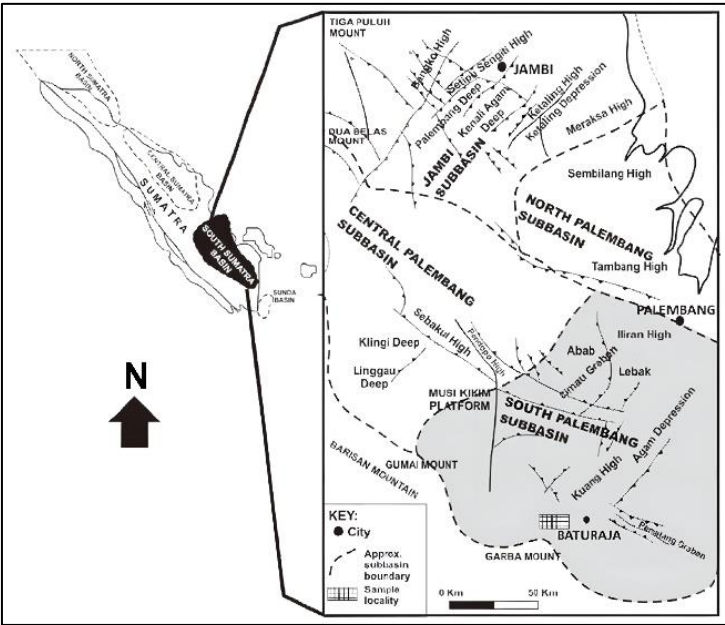


Fig 2. Features of main structural of the South Sumatera Basin

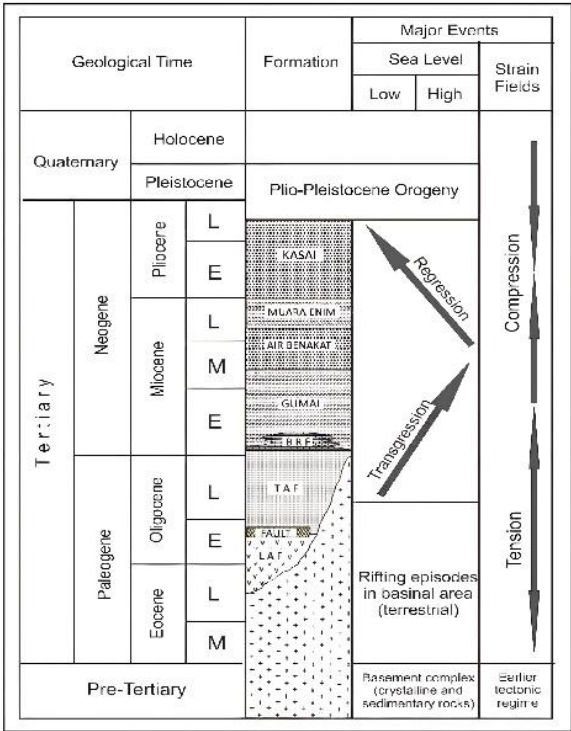


Fig 3. Stratigraphic Architecture of the South Sumatera Basin

The methodology integrates pore pressure, horizontal stress, and rock elasticity models using the Mogi–Coulomb failure criterion. Rock mechanical properties were derived from the relationship between compressional and shear wave velocities and calibrated using the Horsrud correlation. This approach enables accurate mud weight recommendations to maintain well stability.

The developed geomechanical model (MEM) can also be applied to other sedimentary basins with

similar geological challenges such as overpressure and complex fault systems. By integrating wireline logs, pressure tests, and rock property data, this approach enhances drilling safety and efficiency, particularly in data-limited regions, and provides a robust framework for hydrocarbon exploration and well design globally.

Geomechanical evaluation of wellbore stability in complex geological settings is often challenged by limited subsurface data, overpressure zones, and

fault complexity. Conventional approaches frequently fail to define an accurate safe mud weight window due to uncertainties in rock properties, pore pressure, and stress orientation, leading to wellbore instability and drilling inefficiency.

This study proposes a one-dimensional Mechanical Earth Model that integrates wireline logs, pressure tests, rock mechanics correlations, and drilling data into a calibrated geomechanical framework. The model incorporates synthetic shear velocity data, offset well correlations, and the Mogi–Coulomb failure criterion to improve wellbore stability predictions. This methodology provides a comprehensive foundation for defining safe mud weight windows, optimizing drilling parameters, and mitigating risk in the South Sumatra Basin and other similar basins worldwide.

Unlike previous studies that rely on simplified or isolated parameters, this approach combines petrophysical, pressure, and mechanical rock properties with sensitivity analyses on well inclination and rock strength variations to address model uncertainties and improve prediction reliability.

Another key innovation of this study is the transfer of calibrated geomechanical models from data-rich wells (S-3 and S-4) to less-characterized wells (S-8 and S-9). This approach effectively addresses data scarcity by validating model transfer through drilling events and caliper logs, ensuring consistent evaluation of wellbore stability and mud weight optimization. Consequently, the developed framework not only enhances geomechanical understanding in the South Sumatra Basin but also offers a scalable methodology applicable to other geologically complex basins worldwide.

Despite advancements in geomechanical modeling, challenges remain in quantifying the impact of natural fractures, integrating real-time MWD/LWD data, and extending analyses to three-dimensional coupled hydraulic–mechanical processes. Future research should incorporate real-time MEM inversion for adaptive mud weight control, discrete fracture network (DFN) modeling to assess fracture-induced instability, and coupling with reservoir simulations to evaluate drilling impacts on production. Addressing these aspects would further enhance drilling safety, reduce non-productive time, and improve well placement strategies in overpressured and structurally complex reservoirs.

The present study achieves higher predictive accuracy than previous investigations by employing a multi-data calibration strategy that integrates synthetic shear velocity profiles, offset well propagation, and sensitivity analyses within a 1D MEM framework. Previous studies [10], [11] have

demonstrated the potential of MEMs for wellbore stability assessment but often relied on limited log data or idealized failure criteria without addressing uncertainties arising from data scarcity or anisotropic stress conditions. By validating synthetic shear velocity (DTSH) logs with offset well correlations ($R^2 = 0.95$) and calibrating the Mogi–Coulomb criterion using both caliper log breakouts and drilling event records, this research minimizes model bias and establishes narrower, more reliable safe mud weight windows.

Furthermore, the systematic transfer of calibrated geomechanical parameters from data-rich wells (S-3 and S-4) to data-scarce wells (S-8 and S-9) demonstrates a robust methodology applicable to other regions with limited subsurface information. Nevertheless, wellbore instability remains a persistent operational challenge in the South Sumatra Basin due to variations in in-situ stress, pore pressure, and rock strength. Therefore, this study aims to develop a one-dimensional geomechanical model to analyze wellbore stability and determine the safe mud weight window for directional wells in this basin.

2. RESEARCH SIGNIFICANCE

This study introduces a novel one-dimensional geomechanical modelling approach to define safe mud weight windows in the South Sumatra Basin a region characterized by complex geology and limited direct subsurface data. By integrating wireline logs, pressure data, and synthetic shear velocity correlations, the developed model improves the reliability of wellbore stability predictions and enhances drilling safety in data-scarce environments. The transfer of calibrated MEMs between wells demonstrates an effective strategy to optimize drilling design and reduce non-productive time.

While previous 1D MEM studies have shown value in predicting wellbore stability, many assume laterally homogeneous formations and uniform stress regimes, which may oversimplify heterogeneous and faulted reservoirs such as those in the South Sumatra Basin. This research addresses these challenges through calibrated sensitivity analyses and cross-well validation. The findings provide practical insights for improving drilling efficiency and establish a methodological foundation for future extensions into 2D/3D geomechanical modelling and local stress field quantification.

3. MATERIALS

Geomechanical modeling of one dimensional is applied to evaluate in-situ stresses, define safe

mud-weight boundaries, and support drilling path optimization [11]. This modeling method relies on available subsurface data to infer rock strength, pore pressure, and stress conditions [12]. Recent poroelastoplastic formulations have also been applied to capture anisotropic stress distributions around wellbores [13]. Numerical simulations were performed to refine pressure, stress, and mechanical property predictions, resulting in a calibrated predictive framework for drilling operations. The overall workflow consists of the following steps.

1. Collection of primary (field and lab measurements) and secondary (well logs, seismic reports, and previous studies) data
2. Geomechanical analysis, including overburden pressure, pore pressure, rock mechanical properties, and stress-orientation calculations.
3. Numerical modelling and simulation were used to validate the analysis results and predict the geomechanical responses.
4. Model validation using formation pressure data, formation leak-off tests, and laboratory measurements.
5. This approach ensures accurate borehole stability analysis and drilling risk mitigation, with validation conducted by comparing the model predictions with actual drilling data.

One dimensional geomechanical modelling is used to estimate in-situ stresses, define safe mud-weight limits, and support drilling path optimization [14]. This approach relies on available subsurface data to infer rock strength, pore pressure, and stress conditions [14]. Ensuring consistency among all datasets is essential, as integrated interpretation allows key drilling and production issues to be identified and prioritised, enabling efforts to focus on factors that most influence field development outcomes.

When geomechanical properties of a field are evaluated, a systematic workflow is required to assess data quality and quantify associated uncertainties. Any omission in this sequence may introduce inconsistencies or lead to unreliable assumptions in the final interpretation. The construction of the Mechanical Earth Model (MEM), including the testing of alternative modelling approaches, is essential for fully utilizing available geomechanical information [14]. The MEM provides depth-dependent descriptions of rock strength, pore pressure, and in-situ stresses referenced to the stratigraphic column.

The MEM workflow begins with model development in wells S-3 and S-4. The calibrated MEM from S-3 is then propagated to S-8, where wellbore stability (WBS) calculations are performed to determine collapse-related parameters. For well S-9, the MEM from S-4 is extended, and two WBS scenarios are evaluated based on the assumed rock strength of the Pre-Tertiary (PRT) interval. The first case applies the original S-4 rock properties, while the second incorporates the reduced strength parameters derived from the S-8 analysis. Once established, the MEM is used to predict safe drilling margins and guide well-completion decisions for individual wells and broader field development. A simplified representation of the workflow is shown in Figure 4.

3.1 Data Audit and Preparation

A frequent issues in geomechanics studies is the acquisition and consolidation of reliable subsurface data. Developing a Mechanical Earth Model (MEM) requires the integration of multiple datasets to characterize formation strength, stress, and pressure conditions with depth, referenced to the stratigraphic framework [15]. A structured data-gathering workflow is therefore essential to ensure that all required geomechanical inputs are obtained, including density and sonic logs, standard logging suites, multi-arm caliper measurements, borehole image logs, formation tester data, core analyses, drilling reports, mini-frac results, seismic interpretations, NMR and mineralogical logs, as well as real-time information such as LWD and ECD measurements and collapse indicators [16]. For this study, available offset-well data used for geomechanical evaluation include: compressional-wave slowness (DTCO), gamma-ray, bulk-density, and neutron-porosity logs, as well as formation-evaluation parameters such as PHIE, PHIT, and VCL. Formation-pressure information obtained from DST, together with leak-off test (LOT) data and interpreted formation tops, provided essential constraints for pressure and stress calibration. Additional operational inputs, including daily drilling reports (DDR) and two arm caliper measurements. All of the those data were obtained from open-hole logging conducted during drilling operations in wells S-4 and S-3. No logging was performed in the validation well, S-8. For S-8, only the daily drilling report and the geological report were available, documenting drilling activities associated with geomechanical challenges.

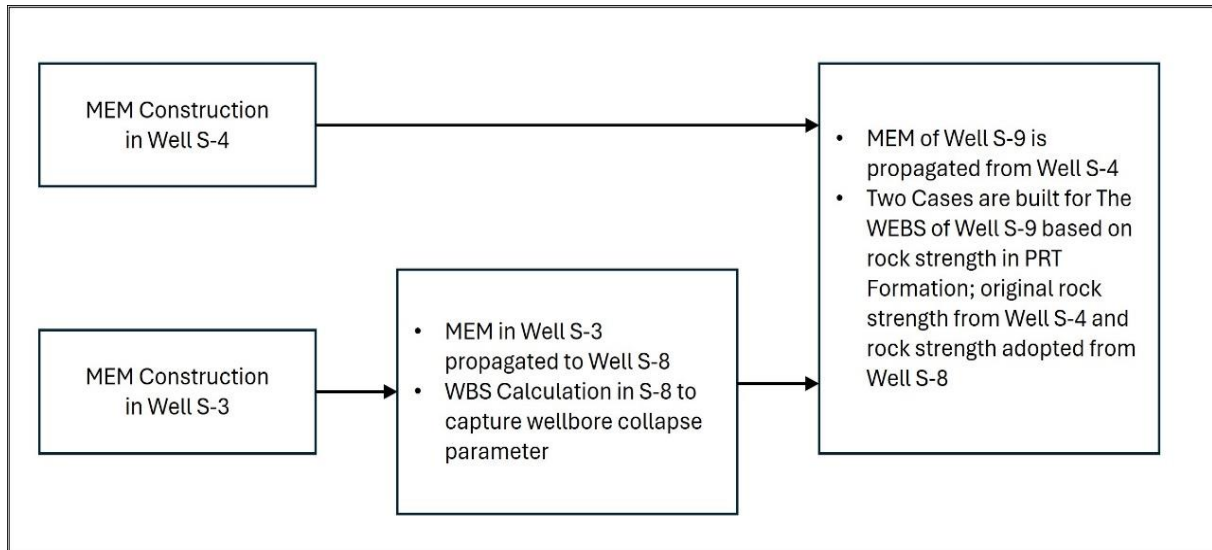


Fig 4. Integrated Workflow for Geomechanical Modelling and Stability Analysis of Well S-9

3.2 Well Data (Logs Data)

Bulk density, compressional velocity, and shear-wave velocity constitute the primary inputs for constructing the 1D Mechanical Earth Model. Although gamma-ray, density–neutron, and sonic logs were available across most intervals, direct shear-wave velocity measurements were not acquired in either well. Consequently, synthetic shear-velocity (DTSH) logs were generated using a DTCO–DTSH correlation derived from the nearby D-7WD well, which contains a full open-hole log suite. The correlation exhibited strong predictive performance ($R^2 = 0.95$), supporting its application to wells S-8 and S-9. The relationship between compressional and shear velocity is illustrated in Figure 5.

The use of a single DTCO–DTSH correlation is widely recognized in geomechanical modelling when direct shear velocity data are unavailable. Previous studies [17], [1], [8]. Have validated this approach for geologically uniform formations. In this study, the synthetic DTSH data produced consistent results with caliper logs and drilling event records, confirming the robustness of the correlation. This method, commonly used in data-scarce environments, provides a practical and scientifically sound solution for reliable MEM construction in the South Sumatra Basin.

3.3. Geomechanical Parameters

The tensile strength was estimated using the empirical relationship $T = UCS/10$, as direct laboratory measurements were unavailable due to limited core recovery and data constraints in the studied wells. This empirical correlation has been widely applied

and validated in previous geomechanical studies for formations with similar lithological and mechanical characteristics. The approach provides a reasonable approximation for input to the Mechanical Earth Model when experimental data are not accessible.

Empirical correlations were also applied to estimate additional rock-mechanical parameters, including cohesion and internal friction angle, because core-laboratory measurements were unavailable. To increase confidence in these estimates, the derived values were validated indirectly by comparing predicted breakout depths and instability intervals with caliper measurements and documented drilling events. The close agreement between modeled results and field observations indicates that the empirical approach provides a reliable representation of the formation's mechanical behavior.

3.4. Mechanical Earth Model Construction Workflow

The Mechanical Earth Model construction workflow included data acquisition, preprocessing, calibration, and validation. The validation process was conducted by comparing the predicted breakout zones and caliper log enlargements with observed drilling data to ensure consistency between modeled and actual wellbore behavior. In addition, the predicted pore pressure profile was cross-checked with Formation Integrity Test, Leak-Off Test, and recorded drilling event data to confirm pressure accuracy. These validation steps confirm the reliability of the constructed Mechanical Earth Model in predicting wellbore stability and demonstrate that the workflow can be systematically replicated for other wells under

similar geological and operational conditions.

4. RESULT AND DISCUSSION

1. Figure 5 displays a cross plot that characterizes the relationship between compressional wave slowness (DTCO) and shear wave slowness (DTSH) obtained from the D-7WD well. In this plot, DTCO ($\mu\text{s}/\text{ft}$) is shown on the horizontal axis, while DTSH ($\mu\text{s}/\text{ft}$) is plotted on the vertical axis. A strong linear correlation between DTCO and DTSH is indicated by the fitted trend line in Figure 5.
2. The trend-line equation, $\text{DTSH} = 32.881 e^{(0.0181 \text{ DTCO})}$, yields a coefficient of determination of $R^2 = 0.9517$, showing that 95.17% of the shear-velocity variability is explained by changes in compressional velocity.
3. Because shear-wave velocity was not directly measured, synthetic DTSH values were generated using the established DTCO–DTSH correlation.
4. A limitation of this approach is the absence of direct sonic-shear measurements for validating the synthetic dataset.

Synthetic shear-wave velocities were evaluated against the available compressional-wave data to assess the DTCO–DTSH correlation. Because shear-sonic logs were not recorded, the comparison relied on the agreement between synthetic DTSH values and measured DTCO trends. The strong correlation in the D-7WD dataset ($R^2 = 0.9517$) indicates that the synthetic shear velocities reliably represent the expected response. Although direct shear-sonic validation was unavailable, the close

match between modeled and measured trends supports the use of the synthetic profile for geomechanical analysis. The use of a single DTCO–DTSH correlation is widely accepted when shear data are limited, and previous studies [17,8] have confirmed its reliability in similar formations. In this study, the D-7WD correlation performed consistently and was applied to wells S-8 and S-9, supported by the stratigraphic uniformity of the Talang Akar Formation. The alignment of the model with caliper logs and drilling events further validates the synthetic DTSH estimates.

Although single-core data can introduce uncertainty, they are acceptable for geomechanical studies in geologically homogeneous formations [1]. In the South Sumatra Basin, the uniformity of the Talang Akar and Baturaja Formations supports this assumption. Calibration was strengthened by integrating core data with well logs and drilling records. The Eaton equation, widely used for pore pressure prediction, was applied with parameters calibrated from nearby wells following industry best practices [14].

Pore pressure calibration was based on multiple datasets, not a single core point. Offset wells S-3 and S-4 provided key inputs density logs, velocity data, porosity, formation pressure, and LOT results used to build a 1D geomechanical model validated with DST data. Breakout modeling was also calibrated using caliper logs and drilling records. For data-limited wells such as S-8, pore pressure models were projected from S-3 and verified through sensitivity analyses of rock strength and inclination effects. This integrated approach produced a robust and validated pore pressure model for the study area.

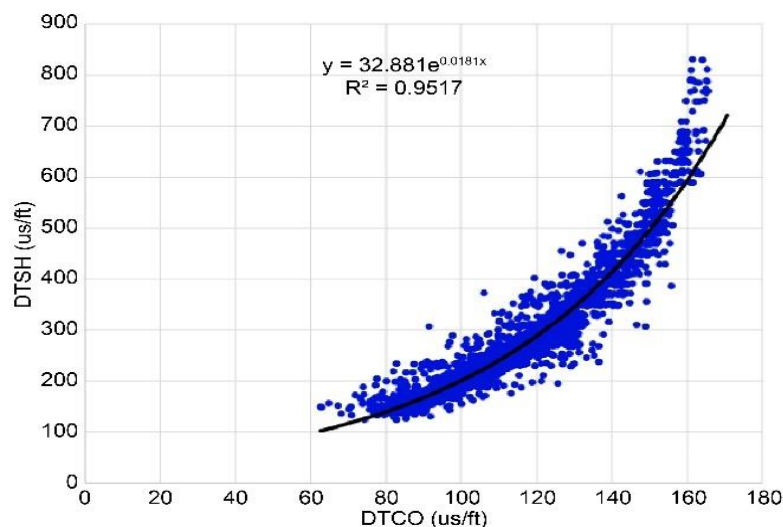


Fig 5. Cross Plot showing a correlation between compressional slowness (DTCO) vs Shear

4.1 Drilling Events Review

A drilling-event review is carried out to evaluate all activities recorded during well operations [18]. An accurate understanding of formation pore pressure is required to ensure safe and cost-effective drilling and to assess risks related to fluid migration and formation stability [19]. This review encompasses all phases of the drilling process, from initial preparation through completion, to improve operational safety and reduce potential hazards.

Overburden stress (σ_v) refers to the pressure acting on a formation at a given depth as a result of the cumulative weight of overlying rocks and fluids. It is calculated by integrating formation density from the surface to total depth using the method of Oloruntobi. In this study, formation density was obtained from wireline and LWD logs, with direct measurements available for most intervals in wells S-3 and S-4.

$$\sigma_v = \int_0^z \rho_b(z) g dz \quad (1)$$

Figure 6 presents the overburden stress calculations for wells S-3 and S-4. The figure includes several curves showing density, vertical pressure, and overburden stress gradients. The red curve in Track 4 represents the extrapolated density, Track 5 displays vertical pressure in psi, and Track 6 shows the overburden stress gradient in ppg.

The analysis shows that the overburden stress patterns in both wells are consistent. The similar curve trends, particularly the linear increase in

vertical pressure with depth in Track 5, indicate that overburden stress increases proportionally with depth. The nearly uniform values of the stress gradient in Track 6 suggest a stable stress distribution. These consistent patterns support the reliability of the dataset and the validity of the resulting geological and geotechnical interpretations.

4.2 Pore Pressure

Pore pressure refers to the fluid pressure within the pore spaces of a formation and is estimated in this study using the Eaton method, which employs compressional-wave velocity as the principal input. [23]. Two trend lines were used to account for the higher organic content in the Talang Akar and PRE-TERTIARY formations. The overpressure zone extends through the Telisa, BRF Equivalent, Pendopo, and Talang Akar Formations. In addition, three pressure inversions were identified in the DTCO model. The pore pressure within the PRT interval was estimated using a gas gradient of 0.1 psi/ft. This assumption was supported by pressure data from well S-3 and a DST measurement of 3794 psi at 2490 mMD in well S-4. The computed pore-pressure profile shows a marked increase within the Telisa and Pendopo formations. Comparison of the calculated pore pressure with the hydrostatic gradient indicates that overpressure begins at roughly 2200 m and intensifies with depth, with pronounced overpressure observed in the Pendopo and LTAF intervals.

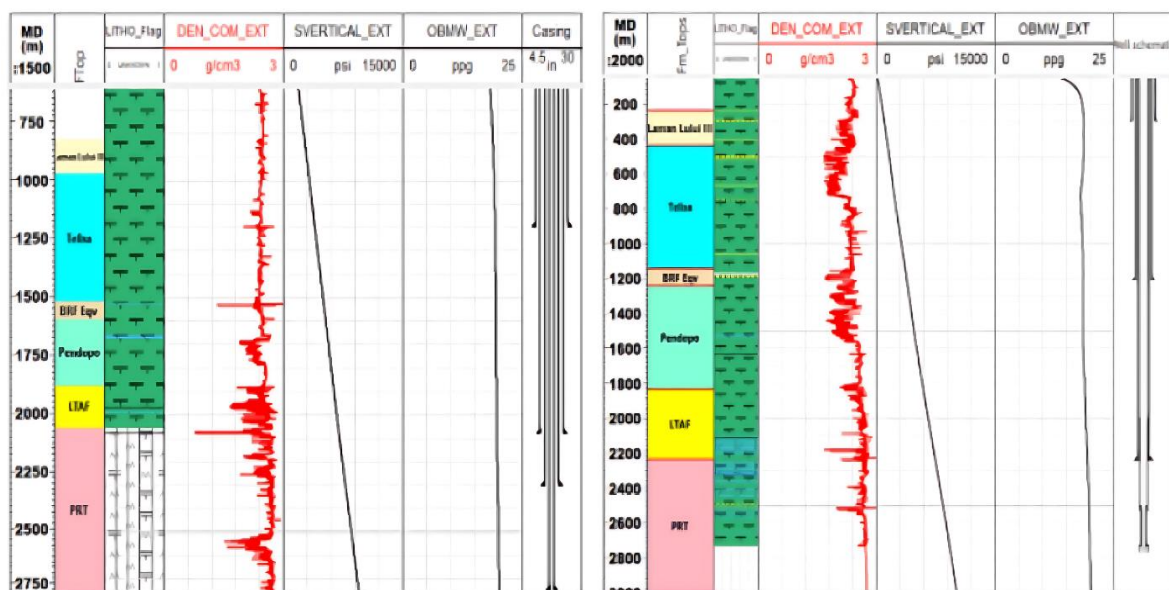


Fig 6. Overburden Stress S-3 (left) dan S-4 (right)

A pore pressure exceeding the hydrostatic pressure suggests a potential overpressure zone that could lead to a borehole instability if not properly managed. The Pressure Measured While Drilling (PPMW) aligned well with the estimated values, indicating the accuracy of the calculation model. A pore pressure pattern similar to that of S-3, with slight differences in overpressure intensity. The overpressure zone begins at a depth of approximately 2100 m, with a significant increase in the Pendopo and LTAF formations. At approximately 2500 m, the pore pressure rises drastically, indicating a more extreme high-pressure zone than that of S-3. The calculated pore pressure (PP) aligned with the measured drilling pressure (PPMW), confirming the reliability of the model estimation. The high-pressure zone in the lower section (below the LTAF) may indicate trapped fluid accumulation, potentially suggesting the presence of hydrocarbon reserves.

Although only one DST point (3794 psi at 2490 mMD in Well S-4) was available, the pore pressure model was further validated by integrating additional indicators such as drilling parameters, mud weight data, and sonic log-derived pore pressure from offset wells. The close agreement among these datasets supports the reliability of the developed pressure model and confirms its regional applicability.

The calculated overburden gradient in this study is approximately 1.0 psi/ft, which aligns well with the typical range reported for Tertiary sedimentary sequences in the South Sumatra Basin (0.95–1.05 psi/ft) [24]. This consistency indicates that the adopted density model and pressure estimation approach are representative of the regional geological framework. The result suggests that the compaction trend of shales and sandstones follows a normal burial compaction profile, commonly observed in Tertiary basins dominated by fine-grained clastic sediments. Additionally, the calculated vertical stress values were cross-verified against regional geomechanical models and previous basin-scale studies, confirming that the overburden stress field behaves in a geologically reasonable manner. This agreement reinforces the reliability of the derived pressure model and supports its applicability for wellbore stability analysis and drilling optimization in similar stratigraphic settings.

The pore pressure model from Well S-3 was applied to Well S-8 based on verified stratigraphic and geophysical similarities between the two wells. Correlation of gamma ray, resistivity, and sonic log responses confirmed consistent lithological sequences and formation tops, particularly within the Talang Akar and Pendopo formations. Although minor depth shifts were observed, the overall

compaction trends and pressure gradients were comparable. This correlation justifies the transfer of the pore pressure model and supports its validity for regional application within the same depositional environment.

4.3 Rock Parameters

Elastic parameters—including Young's modulus, Poisson's ratio, shear modulus, and bulk modulus—define the elastic deformation response of the rock and serve as essential inputs for estimating rock strength and in-situ stress conditions [25]. Dynamic elastic properties in this study were derived from compressional and shear sonic logs together with bulk-density logs, using equations adapted from the method of Bozorgi [26].

$$G_{dyn} = 13474.45 \frac{\rho_b}{(\Delta t_b)^2} \quad (2)$$

$$K_{dyn} = 13474.45 \rho_b \left[\frac{1}{(\Delta t_b)^2} \right] - \frac{4}{3} G_{dyn} \quad (3)$$

$$E_{dyn} = \frac{9 G_{dyn} K_{dyn}}{G_{dyn} + 3 K_{dyn}} \quad (4)$$

$$\nu_{dyn} = \frac{0.5(\Delta t_s/\Delta t_c)^2 - 1}{(\Delta t_s/\Delta t_c)^2 - 1} \quad (5)$$

For geomechanical modelling in this field, static elastic properties obtained from rock-mechanics testing are typically required. Because direct laboratory measurements were not available, representative values from the nearest field were adopted. Static Young's modulus was estimated from compressional velocity using the Horsrud correlation [26], while static Poisson's ratio was taken as 0.9 of the dynamic value. Although not directly validated by core testing, these empirical correlations are widely accepted for estimating rock properties under comparable geological conditions. The use of dynamic elastic parameters [27] to infer static values is also standard practice and generally provides sufficient accuracy for geomechanical analysis.

Rock strength parameters were derived from the unconfined compressive strength (UCS). For the Laman Lului III through LTAF intervals, UCS was estimated using the Horsrud equation, whereas the PRE-TERTIARY formation values were calculated using the Coates–Denoo correlation based on static Young's modulus, bulk modulus, and shale volume. The friction angle was determined using the Lal correlation, and tensile strength (TSTR) was taken as one-tenth of the UCS [28].

Empirical UCS estimates from nearby fields are valid when direct tests are unavailable and formations are geologically similar. Sensitivity analyses were performed to reduce uncertainty. Previous studies [25,27,28] confirm that UCS derived from velocity-based correlations provides reliable results across comparable formations.

The mechanical well log includes depth, formation tops, wellbore orientation, stratigraphy, bit size, caliper, gamma-ray response, sonic velocities, density, porosity, elastic moduli, tensile strength, UCS, friction angle, and true vertical depth. Deeper formations, particularly the Pre-Tertiary interval, exhibit higher UCS, tensile strength, and friction angles, indicating greater stability. Overall, well S-4 shows stronger mechanical properties than S-3, affecting drilling behavior and reservoir management.

4.4 Horizontal Stress Profile

No direct studies have determined the horizontal stress orientation in the S field or nearby areas. Therefore, this study adopts the regional stress map [28], shown in Figure 11, indicating a NE–SW maximum horizontal stress ($\sim 135^\circ$ NW–SE). Although less ideal in tectonically active zones, regional stress maps remain reliable when regional patterns align with the tectonic setting [29]. Combined with pore pressure and drilling data, this approach has proven to significantly improve wellbore stability [30].

Several studies [8,10] have shown that in regions lacking local stress data, regional stress orientation

derived from geophysical surveys or tectonic models provides a strong foundation for geomechanical analysis. In Indonesia, regional stress orientation has been successfully used for preliminary predictions of wellbore stability and drilling safety, especially in formations influenced by large-scale tectonic trends. While local faulting introduces some uncertainty, integrating regional stress maps with structural and geophysical data offers a practical and effective method for stress prediction in complex geological environments.

Using the calculated vertical, minimum horizontal, and maximum horizontal stresses, the study identifies the formation's stress regime [9]. To estimate the horizontal stresses, the analysis applies a poroelastic model that incorporates geothermal and tectonic strain effects [30]. When thermal influences are ignored, this poroelastic formulation simplifies into an expression that yields both the minimum and maximum horizontal stress magnitudes.

$$\sigma_h = \frac{\nu}{1-\nu} \sigma_v + \frac{1-2\nu}{1-\nu} \alpha P_p + \frac{E}{1-\nu^2} \epsilon_x + \frac{\nu E}{1-\nu^2} \epsilon_y \quad (6)$$

$$\sigma_H = \frac{\nu}{1-\nu} \sigma_v + \frac{1-2\nu}{1-\nu} \alpha P_p + \frac{E}{1-\nu^2} \epsilon_y + \frac{\nu E}{1-\nu^2} \epsilon_x \quad (7)$$

This formulation provides a mathematical basis for estimating horizontal stress magnitudes without direct field measurements, while incorporating strain effects associated with geothermal gradients and regional tectonic deformation. [31].

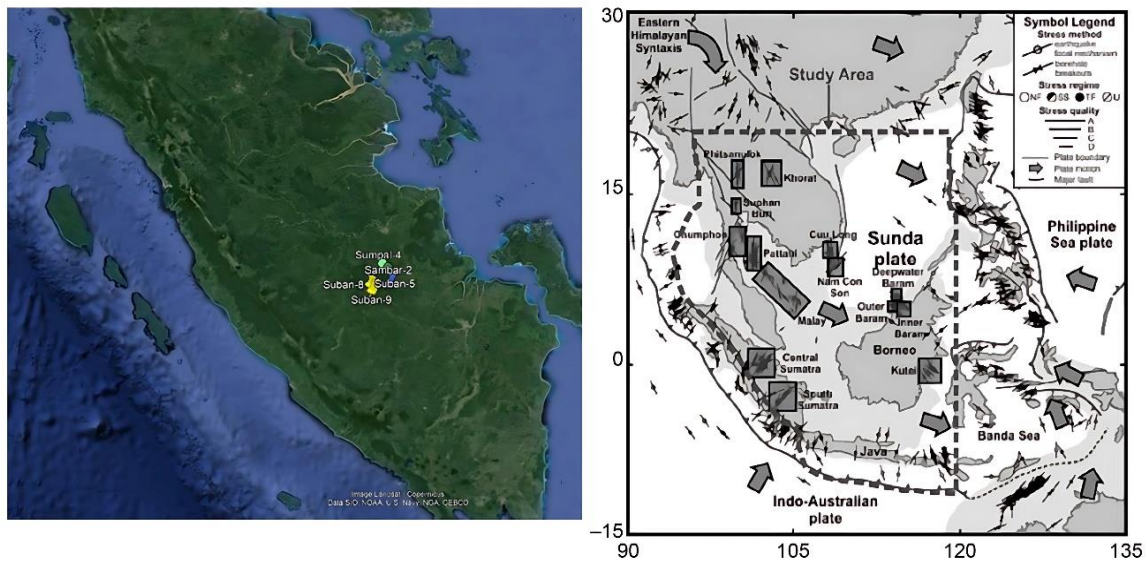


Fig 7. Horizontal Stress

4.5 Wellbore Stability Analysis

A wellbore stability analysis was performed to validate the MEM, which represents the in-situ stress state and rock mechanical properties for each stratigraphic interval [32]. The shear-failure breakout model (Track 11) was evaluated against caliper measurements (Track 12) to confirm borehole enlargement patterns. In well S-3, the breakout model aligned closely with the caliper log and documented instability events, such as narrow-hole conditions. A similar match was observed in well S-4, where the modeled breakout depths and severities corresponded well with caliper enlargements and instability indicators. These results show that the breakout model can reliably predict the location and magnitude of wellbore breakouts [33]. Although the analysis relies on single-arm caliper data, which cannot fully distinguish directional breakout from washout, the consistency observed between the modeled and measured borehole enlargements still supports the interpretation of breakout-related deformation. This interpretation is justified because the enlargement patterns, when integrated with drilling event records and MEM stress calibration, show trends consistent with typical breakout behavior reported in previous geomechanical studies. Although it is true that a 4-arm caliper or image log provides more detailed data for differentiating breakout from general borehole enlargement, previous studies have shown that using a single caliper log for calibrating horizontal stresses can still provide reliable estimates for wellbore stability analysis. For example, research demonstrated that even with the use of a single caliper log, if complemented by other geomechanical data such as pore pressure logs and drilling records, reliable results can be achieved [34]. Furthermore, some research highlighted that in cases where field data are limited or difficult to obtain, a single caliper measurement can still offer sufficiently accurate results for predicting wellbore stability, particularly when integrated with other geomechanical models and sensitivity analysis [10]. These studies suggest that, while a more detailed tool is preferred, a single caliper log remains a valid method in situations where additional data sources are available to support the analysis.

A research demonstrated that a single caliper is effective in detecting borehole enlargement caused by breakout, especially when significant diameter changes occur [18]. Further demonstrated that repeated analyses or combining caliper data with additional inputs can accurately distinguish normal enlargement from breakout [12]. Research emphasized that integrating caliper data with image

logs or pressure and temperature measurements enhances the detection accuracy, particularly in complex conditions [11]. Similarly, a research highlighted that although a single caliper may struggle with finer breakouts, its combination with historical data and additional observations makes it valuable for horizontal stress calibration and breakout detection [22].

While criticism regarding the improper calibration of horizontal stress using borehole breakout is acknowledged, several previous studies have shown that these recommendations can still serve as a benchmark. The use of the regional stress direction as a substitute for local field data, although not ideal, is still acceptable in many cases. Some research demonstrated that in regions with significant tectonic activity, regional stress maps can provide sufficiently accurate information, even without complete local data, particularly when similar geological conditions exist between the analysed areas [10], [35]. Additionally, although the use of a single caliper log has limitations in accurately detecting borehole breakout, some research showed that a single caliper can still provide strong indications of borehole enlargement caused by breakout [12], [18]. By combining historical data with consistent geomechanical models, as explained [22], the recommendations presented in this study remain valid. Despite the uncertainties related to local calibration and breakout measurements, these recommendations can still be used as reliable starting points for drilling planning and wellbore stability analysis. Thus, although the reliance on regional data and single caliper usage is valid, this analysis still provides adequate results supported by additional data, geomechanical models, and consistent measurement trends. This alignment suggests that the breakout model is effective for interpreting wellbore behavior, although some wellbore wall damage may remain undetected during drilling if the failed material temporarily supports the borehole. [36].

The wellbore prediction results for the curtain section of well S-8 indicate that no direct log data were available from S-8 or its lateral sections. Consequently, log inputs from the 1D MEM—including DTCH, DTSH, RHOB, elastic properties, and rock-strength parameters derived from well S-3—were propagated to S-8 for the wellbore stability analysis [10]. This approach transfers calibrated log and mechanical properties from S-3 to model the expected subsurface conditions in S-8, providing a practical solution in the absence of local measurements. Utilizing data from the nearest offset well is essential for generating a reliable representation of the geological and mechanical

behavior at S-8.

Further limitations in the calibration of S-8 were addressed by maintaining consistent parameter inputs across all supporting wells and adjusting the breakout model using caliper data and documented drilling events. To represent the influence of natural fractures within the PRE-TERTIARY interval, the rock strength was reduced by applying a 30% UCS scaling (average ≈ 3708 psi), assigning a tensile strength equal to 0.1 of the reduced UCS, and decreasing the internal friction angle to 60% of its original value (average $\approx 24.6^\circ$). The resulting breakout model for S-8 showed strong agreement with observed instability events, including a pack-off at 2138 mMD. These validated reductions in rock strength were subsequently adopted as the low-case scenario for the wellbore stability analysis of S-9.

Wellbore stability is a critical factor governing drilling safety and operational efficiency. The analysis highlights the importance of accurately characterizing rock and geological conditions to mitigate the risk of failure during drilling [34]. The simulated reduction in rock strength to represent natural fracturing within the PRE-TERTIARY formation further underscores the need for detailed understanding of local geological controls [35]. The strong agreement between the S-8 breakout model and recorded drilling events demonstrates the model's reliability in predicting wellbore behavior. Applying these validated parameters to subsequent wells, such as S-9, reflects a systematic and evidence-based approach to reducing operational risk and enhancing drilling performance.

The curtain section and wellbore prediction model for S-9 were developed using S-4 as the reference well, given its proximity and expected geological similarity to the planned trajectory. The modeling utilizes a full suite of 1D MEM inputs—including DTCO, DTSH, RHOB, elastic properties, and rock-strength parameters—to represent the geomechanical conditions along the S-9 path. For this well, pore pressure, horizontal stress, and pressure loads were recalculated to reflect local variations in subsurface conditions. Selecting S-4 as the reference enhances the accuracy of MEM propagation, as nearby wells typically share comparable lithological and mechanical characteristics [37]. The recalculated pressure and stress parameters provide a more representative subsurface model, supporting improved identification of potential instability risks and ensuring adequate wellbore stability throughout drilling and production.

The wellbore stability analysis and mud-weight recommendations for S-9 indicate that the pore-pressure model includes a 1600-psi pressure

drop within the PRT formation. Two scenarios were evaluated: the first applied the original S-4 rock-strength parameters across the entire interval, whereas the second incorporated reduced PRT rock strength to reflect the fracture-related weakening observed in S-8. In Case 2, the UCS was reduced to 30% of its original value, tensile strength was set to 0.1 of the reduced UCS, and the internal friction angle was decreased to 60% of the baseline value, representing a more fractured and mechanically weaker formation relative to Case 1. Suboptimal mud-weight design can lead to borehole enlargement and instability [38]; therefore, mud-weight recommendations were derived by assessing shear-failure risk for each scenario. These recommendations generally follow the 0% Depth-of-Damage trend, though in certain intervals they fall below the shear-failure gradient to maintain operational safety. A sensitivity analysis was performed to evaluate the influence of inclination and azimuth on the safe mud-weight window [39]. The results emphasize the importance of accurate pore-pressure estimation, appropriate rock-strength selection, and mud-weight design in ensuring the stability of S-9. The two-case strategy demonstrates a rigorous and conservative approach to managing potential collapse risk.

4.6 Sensitivity Analysis

The results in Figure 8 show that sensitivity analysis is essential for evaluating wellbore stability under varying geological and operational conditions. Well deviation strongly influences the mud-weight response, as increasing deviation narrows the safe MW window due to higher shear-failure gradients. For the PRT formation, the analysis recommends a maximum deviation of 30° , as no stable mud-weight window exists beyond this limit in Case 2. Maintaining a deviation below 30° therefore ensures an acceptable MW window for both scenarios.

The sensitivity analysis further underscored the critical influence of rock-strength variability and in-situ stress conditions on wellbore stability. Within the PRT formation, the stability evaluation revealed a high susceptibility to shear failure, particularly under the reduced-strength conditions represented in Case 2. To mitigate instability, drilling under controlled mud-loss conditions is recommended, as this approach minimizes the likelihood of pack-off or collapse. Continuous surveillance of cuttings and early indicators of wall failure remains essential, and incremental increases in mud weight should be implemented only when collapse signatures are observed. The acquisition of comprehensive logging data—including direct shear-wave velocity

measurements using advanced sonic tools—is strongly recommended to reduce uncertainties associated with synthetic shear-velocity estimates and to improve the robustness of the Mechanical Earth Model. The wellbore stability assessment is supported by Schmidt-type contour plots that delineate the critical mud-weight and ECD thresholds for breakout and breakdown across varying azimuths and inclinations. These visualizations provide quantitative constraints for mud-weight design and casing-point selection during trajectory planning. Within the mud-weight analysis, the stereonet plot functions as a directional stability reference, illustrating the pronounced sensitivity of breakout risk to deviations in well inclination and azimuth. The mud-weight window plot further highlights the boundaries for breakout and crack initiation, with yellow and dark-blue zones defining the minimum and maximum mud-weight requirements for maintaining stability. The intervening white region delineates the operationally stable mud-weight window as a function of trajectory orientation, thereby supplying essential guidance for drilling program optimization.

5. CONCLUSION

This research employs geomechanics modelling and borehole stability analysis to establish the safe mud-weight requirements in the South Sumatra Basin. The breakout model was calibrated and validated using caliper measurements and

documented drilling borehole issues, demonstrating its effectiveness in predicting both the depth and severity of breakout development. The calibrated Mechanical Earth Models from wells S-3 and S-4 were subsequently propagated to wells S-8 and S-9 to evaluate and mitigate potential borehole problem along their trajectories. A key component of this workflow involved transferring the validated S-8 parameters to S-9, with adjustments applied to account for the reduced rock strength observed in the PRT formation. This refinement constitutes an essential step in ensuring that the propagated model reflects the mechanical conditions governing wellbore behavior in the deeper fractured interval.

The wellbore stability assessment for S-9 integrates the full suite of 1D MEM inputs, including pore-pressure profiles, horizontal-stress estimates, and formation pressure loads. Pore pressure was modeled by incorporating the observed pressure drop within the PRE-TERTIARY formation, and two rock-strength scenarios were evaluated: one applying the original S-4 strength parameters and another incorporating reduced PRE-TERTIARY strength consistent with the instability inferred from S-8. Mud-weight recommendations were derived by evaluating the planned trajectory and minimizing the predicted shear-failure risk across both scenarios. A sensitivity analysis was performed to assess the influence of inclination and azimuth on the operational mud-weight window, identifying directional conditions that could expand the stability envelope.

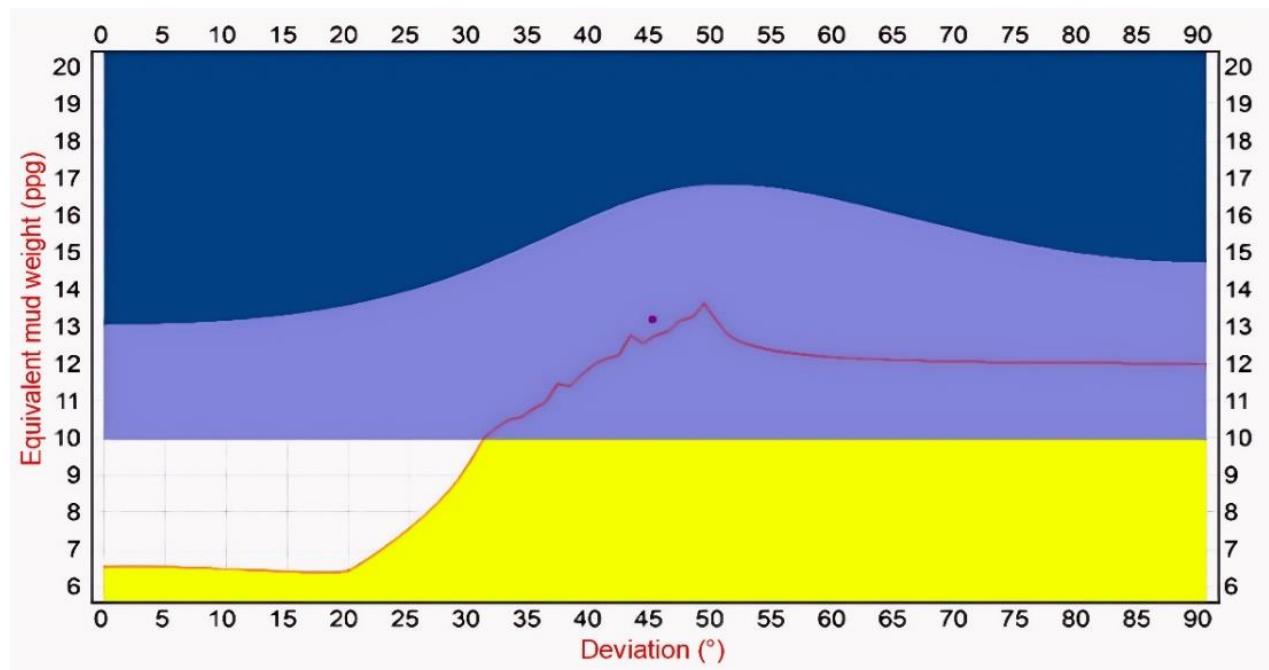


Fig. 8 Sensitivity Analysis PRT Formation Cases 1 and 2

The results have important implications for characterizing the mechanical behavior of the formations encountered in the South Sumatra Basin. The analysis highlights the need to incorporate natural-fracture effects, refine geomechanical modeling approaches, and develop improved techniques for constraining the safe mud-weight window. Overall, the study provides a strengthened geomechanical framework for reducing drilling risk and improving wellbore stability in structurally complex and overpressured sedimentary environments.

The findings of this study have practical implications for drilling operations in the South Sumatra Basin. The developed Mechanical Earth Model and wellbore stability analysis can be directly used to optimize mud weight design, select safe well trajectories, and minimize the risk of borehole collapse. The recommended maximum inclination of 30° and calibrated pressure windows provide engineers with quantitative guidelines for safer and more efficient drilling programs. These results can also serve as a reference for geomechanical planning in similar Tertiary sedimentary environments.

In conclusion, this study provides a comprehensive geomechanical framework that enhances understanding of wellbore stability in the South Sumatra Basin. The integration of field data, mechanical modeling, and sensitivity analysis demonstrates an effective workflow for managing drilling risks in complex geological settings. The insights gained from this research can guide future studies in refining regional Mechanical Earth Models and developing advanced real-time wellbore monitoring systems to further improve drilling safety and efficiency.

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