



EGS STIMULATION DE-RISKING STRATEGY: IDENTIFICATION OF A SHALLOW MECHANICAL “SWEET SPOT” IN THE UTAH FORGE GRANITOID USING INTEGRATED PETROPHYSICAL ANALYSIS

Tedi Ardiasyah¹

¹ Department Geological Engineering, Jenderal Soedirman University

* Corresponding author : t.tediardiasyah@gmail.com

Received: Dec 1, 2025; Accepted: Jan 31, 2026.

DOI:

Abstract

High confinement stress and ductile failure modes frequently hinder the formation of complex fracture networks in deep Enhanced Geothermal Systems (EGS). This study proposes an operational de-risking strategy by characterizing the shallow transition zone at the Utah FORGE site. Integrating dipole sonic logs and drilling parameters from pilot well 58-32 and offset well 16A(78)-32, we applied robust P10-P90 statistical normalization to identify a mechanical "sweet spot." A highly brittle interval was defined at 3,892 ft (Brittleness Index > 0.82; Young's Modulus > 75 GPa). Lateral validation in the offset well confirms regional continuity, evidenced by spectral uranium anomalies (> 3 ppm)—interpreted as a signature of secondary mineral precipitation along permeable fracture pathways—and distinct drilling breaks indicated by a significant drop in Mechanical Specific Energy (MSE) (< 20 kpsi)—revealing a permeable natural fracture corridor. In sharp contrast to the semi-ductile deep reservoir (> 7,000 ft; BI < 0.46), this shallow brittle interval offers an optimal, lower-risk candidate for Diagnostic Fracture Injection Tests (DFIT) to calibrate stimulation parameters before targeting the high-risk deep basement.

Keywords: Utah FORGE, EGS De-Risking, Brittleness Index, Lateral Validation, Mechanical Sweet Spot, Robust Normalization

1. Introduction

1.1 Background

Enhanced Geothermal Systems (EGS) represent a pivotal frontier in renewable energy, designed to unlock the immense thermal potential within hot, low-permeability basement rocks that conventional hydrothermal systems cannot reach. Unlike traditional reservoirs where permeability is natural, the success of EGS hinges entirely on reservoir stimulation—the engineering process of creating a complex, conductive fracture network capable of circulating fluids for heat exchange (Zoback, 2007). The Utah Frontier Observatory for Research in Geothermal Energy (Utah FORGE), funded by the U.S. Department of Energy (DOE), serves as the premier global field laboratory for this technology. Development at Utah FORGE primarily targets granitoid formations at depths exceeding 6,000 ft (1.8 km), where reservoir temperatures surpass 175°C (Allis et al., 2019).

However, a fundamental geomechanical paradox exists. While greater depth provides higher

temperatures, it also imposes extreme confining stresses (>40 MPa). Previous studies indicate that under these conditions, granitic rocks undergo a brittle-to-ductile transition. Instead of snapping crisply to form open fractures, the rock behaves semi-plastically, absorbing hydraulic energy. Stimulation in this ductile regime carries severe technical risks, such as the formation of simple, short planar fractures that rapidly close when pressure is released, or "screen-out" events where proppant fails to enter the fracture, halting operations. These failures carry massive financial implications. Deep well interventions require high-pressure pumping fleets and prolonged rig time, costing millions of dollars. Therefore, executing full-scale stimulation in the deep reservoir without a validated predictive model is akin to "flying blind" with high capital risk.

To mitigate these risks, this study proposes a "Step-wise De-Risking Strategy" by repositioning the under-utilized shallow transition zone (< 5,000 ft) as an operational pilot test bed. Identifying a shallow interval that possesses highly brittle mechanical characteristics—yet resides within a lower stress regime—is critical. This zone

effectively functions as an "in-situ mechanical laboratory" where hydraulic parameters (e.g., breakdown pressure, fluid leak-off, and proppant transport) can be calibrated under controlled conditions. Validating stimulation designs in this safer, lower-cost shallow environment provides the engineering confidence needed before targeting the high-risk deep basement.

Specifically, this study addresses **three key objectives**: (1) To identify a Mechanical Sweet Spot in the shallow interval of **Pilot Well 58-32** using integrated wireline logs; (2) To validate the permeability of this zone using independent physical indicators, specifically spectral uranium anomalies (which serve as tracers for paleo-fluid flow) and drilling efficiency metrics (MSE); and (3) To quantitatively contrast the brittleness profile of the shallow zone against the deep reservoir to justify the necessity of a shallow pilot test.

This research offers distinct **novelty** compared to existing literature (e.g., Xing et al., 2020; Wang & Stewart, 2024) which predominantly focuses on the deep reservoir. By applying a **robust P10-P90 statistical normalization to Rickman's Brittleness Index**, this study eliminates data distortion caused by borehole rugosity, offering a more accurate evaluation of rock quality. Furthermore, it provides the first direct evidence that the shallow zone is not merely "overburden", but a strategic asset for de-risking the entire EGS development lifecycle.

2. Geological Setting And Theoretical Framework

2.1 Geological Setting of Utah FORGE

The Utah FORGE site is located in the southeastern Milford Basin, Beaver County, Utah, physiographically situated in the transition zone between the Colorado Plateau and the Basin and Range Province. This area was selected by the DOE due to its ideal thermal and lithological characteristics as a representative basement EGS reservoir (Moore et al., 2019).

The stratigraphy is dominated by thick Quaternary alluvium overlying crystalline basement. Data from well 58-32 indicates the contact between Tertiary alluvium/volcanics and the granitoid basement occurs at depths of approximately 2,100–2,500 ft. This basement is part of the Mineral Mountains Intrusive Complex (MMIC), composed of Miocene Diorite, Granodiorite, and Granite (Nielson et al., 2017). Structurally, the stress regime is controlled by Basin and Range extension, with the minimum horizontal stress ($S_{h_{min}}$) oriented East-West (105°). The geothermal gradient is high, reaching $70^\circ\text{C}/\text{km}$, with reservoir temperatures at 6,000 ft exceeding 175°C .

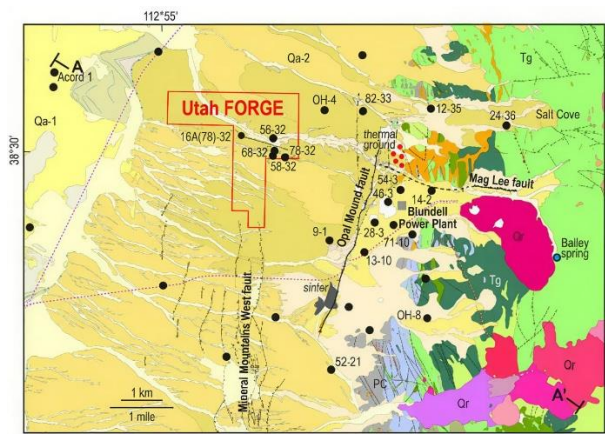


Fig. 1. Geologic map of the FORGE site and surrounding area (modified from Nielson et al. 1986 and Kirby et al., 2018). Abbreviations: Qa-1=Lake Bonneville mud and sand; Qa-2=alluvial fan deposits; Qr=Quaternary rhyolite lava and pyroclastic deposits; Tg=Tertiary granitoids; PC=Precambrian gneisses; Filled black circles=wells.

These geological conditions present the primary challenge. Although temperatures are sufficient, the matrix permeability of the granitoid is extremely low ($\sim 10 \mu\text{D}$). Consequently, energy extraction relies entirely on the creation of artificial permeability through hydraulic stimulation.

2.2 The Concept of Brittleness in EGS Stimulation

Hydraulic stimulation success is governed by rock mechanics, particularly brittleness. In reservoir geomechanics, brittleness is defined as the rock's ability to undergo failure without significant prior plastic deformation (Zoback, 2007). Rocks with a high Brittleness Index (BI) tend to form complex fracture networks when hydraulically pressurized, which is crucial for maximizing heat exchange surface area in EGS. Conversely, ductile rocks tend to absorb deformation energy, resulting in simple planar fractures or fracture initiation failure (**ballooning effect**). Depth plays a vital role in this behavior; increased confining stress and temperature can shift rock behavior from a brittle to a ductile regime. This phenomenon poses a major risk in deep EGS development and is often overlooked in static models.

2.3 Quantitative Geomechanical Methodology

To characterize brittleness profiles from wireline logs, this study adopts the mineralogy and elasticity approach proposed by Rickman et al. (2008), modified with robust normalization techniques.

2.3.1 Dynamic Elastic Moduli

Elastic properties are calculated using compressional wave velocity (V_p), shear wave velocity (V_s), and bulk density (ρ_b). Dynamic Young's Modulus (E_{dyn}) and Poisson's Ratio (ν_{dyn}) are derived using standard elastic equations.

$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

$$E_{dyn} = \frac{\rho_b V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2}$$

2.3.2 Rickman's Brittleness Index

Rickman's method combines Young's Modulus (stiffness) and Poisson's Ratio (resistance to lateral deformation) to calculate the Brittleness Index (BI). Brittle rocks are characterized by high Young's Modulus and low Poisson's Ratio.

$$BI = \frac{E_n + \nu_n}{2}$$

Where E_n and ν_n are the normalized moduli.

2.3.3 Robust Statistical Normalization (P10-P90)

Instead of using standard Min-Max normalization, which is sensitive to outliers or cycle-skipping, this study applies Truncated Normalization as recommended by **Perez & Marfurt (2014)**.

$$E_n = \frac{E_{cal} - E_{P10}}{E_{P90} - E_{P10}}$$

$$\nu_n = \frac{\nu_{P90} - \nu_{cal}}{\nu_{P90} - \nu_{P10}}$$

Normalization limits are determined based on the 10th (P10) and 90th (P90) percentiles of the data distribution in the reference well (**Pilot Well 58-32**). This ensures the resulting BI values represent the intrinsic properties of the clean formation, free from borehole washout effects.

3. Methodology

3.1 Data Inventory and Quality Control

The primary dataset is sourced from the Geothermal Data Repository (GDR). This study integrates data from three key wells representing the vertical profile from surface to basement:

- **Well 58-32 (Pilot):** Dipole Sonic, Density, Neutron, Spectral GR.
- **Well 16A(78)-32 (Injector):** ThruBit Sonic, Composite Log.
- **Well 78B-32 (Monitor):** Advanced Geomechanics Log.

Prior to analysis, all raw logs underwent rigorous Quality Control (QC). Intervals with poor borehole conditions (washout > 2 inches) or cycle-skipping were eliminated to prevent interpretational bias.

3.2 Dynamic Elastic Moduli Characterization

Geomechanical parameters were calculated based on linear elasticity principles. Given the target formation is tight granitoid with negligible

matrix porosity (< 2%), isotropy assumptions were used for dynamic moduli calculations (**Zoback, 2007**).

$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

$$E_{dyn} = \frac{\rho_b V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2}$$

Where V_p and V_s are converted from log slowness data (Δt_c and Δt_s).

3.3 Brittleness Modeling

To identify zones supporting complex fracture initiation, the Brittleness Index (BI) was modeled. Rickman's method combines Young's Modulus (stiffness) and Poisson's Ratio (resistance to lateral deformation) to calculate the Brittleness Index (BI).

$$BI = \frac{E_n + \nu_n}{2}$$

Where E_n is the normalized Young's Modulus and ν_n is the normalized Poisson's Ratio.

3.4 Robust Normalization (P10-P90)

Instead of using standard Min-Max normalization, which is sensitive to outliers, this study applies Truncated Normalization as recommended by **Perez & Marfurt (2014)**. Normalization limits are determined based on the 10th (P10) and 90th (P90) percentiles of the data distribution. This ensures the resulting BI values represent the intrinsic properties of the clean formation, free from borehole washout effects.

To mitigate instrument noise sensitivity, the normalization limits $E_{P10}=30$ GPa, $E_{P90}=76$ GPa, $\nu_{P10}=0.22$, $\nu_{P90}=0.33$ were derived from the vertical pilot well (58-32) and applied as a Global Baseline across all wells. This ensures an "apple-to-apple" comparison and removes anisotropy effects potentially present in the deviated well (16A).

$$E_n = \frac{E_{cal} - E_{P10}}{E_{P90} - E_{P10}}$$

$$\nu_n = \frac{\nu_{P90} - \nu_{cal}}{\nu_{P90} - \nu_{P10}}$$

3.5 Natural Fracture Validation

BI calculations were cross-validated with physical indicators of fracturing:

1. **Spectral Gamma Ray:** Uranium (U) concentration serves as a permeability proxy. In crystalline rocks, uranium anomalies are often associated with secondary mineral precipitation along open fractures that facilitated paleo-fluid flow.
2. **Mechanical Specific Energy (MSE):** Drilling efficiency was calculated using

Teale's Equation (1965). A drastic drop in MSE ("drilling break") is interpreted as rock weakened by natural fracturing.

$$MSE = \frac{WOB}{A_b} + \frac{120\pi \cdot N \cdot T}{A_b \cdot ROP}$$

Where WOB is the weight on the bit, N is the rotational speed (RPM), T is the torque, and A_b is the area of the bit.

3.6 Research Flowchart

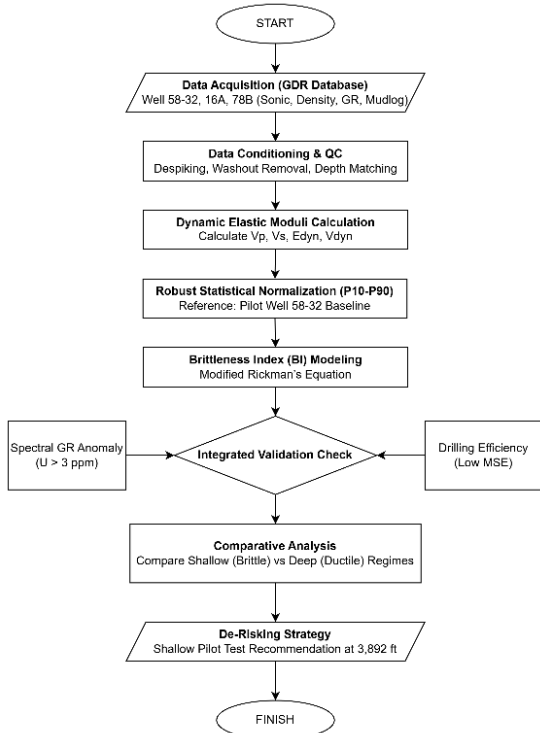


Fig. 2. An integrated research workflow was adopted in this study. This methodology emphasizes robust statistical normalization (P10-P90) obtained from pilot wells (58-32) to establish a global baseline for multi-well fragility characterization and valid sweet spot identification.

4. Results

4.1 Geomechanical Characterization of the Pilot Well (58-32)

Wireline logs evaluation of vertical well 58-32 focused on the upper granitoid interval from 2,500 ft to 5,000 ft. Application of **robust statistical normalization (P10-P90)** to the Brittleness Index (BI) calculation revealed significant rock mechanics variations along the borehole.

Well 58-32 (MU-ESW1) - Optimized Scale

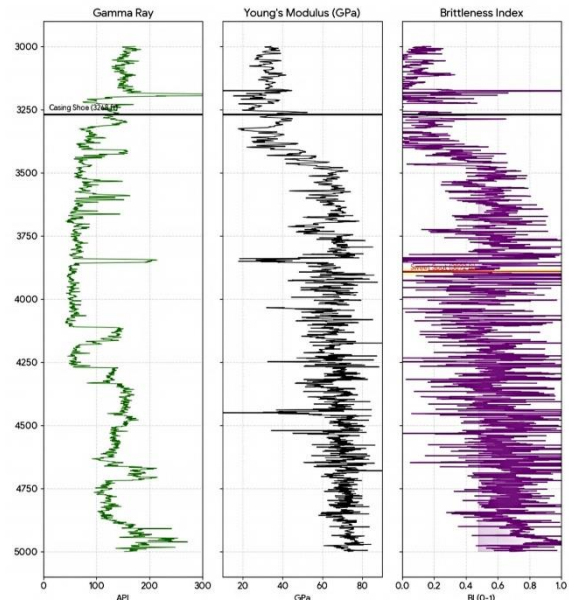


Fig. 3. Geomechanical profile of pilot well 58-32 (3,000–5,000 ft). The yellow highlight at 3,892 ft shows the identified shallow optimum, characterized by a high brittleness index ($BI > 0.82$) and high stiffness, which is located safely below the casing shoe (3,268 ft).

As shown in Fig. 3, the majority of the bedrock interval exhibits intermediate mechanical behavior, with BI values ranging from 0.45 to 0.60. However, a distinctive positive anomaly is clearly identified at depths of 3,892 ft to 3,922 ft (~30 ft thick).

This zone, hereafter referred to as the "Shallow Target Zone," exhibits highly brittle mechanical characteristics with the following key parameters:

- **Brittleness Index (BI):** Average > 0.82 , with peak values reaching 0.91. This value far exceeds the commonly used brittle-ductile transition threshold ($BI \approx 0.45-0.50$).
- **Young's Modulus (E_{dyn}):** Average > 75 GPa, indicating high rock stiffness, ideal for maintaining fracture apertures.
- **Poisson's ratio (ν_{dyn}):** Low (< 0.23), which minimizes the effects of lateral deformation during loading.

Operationally, this zone is located approximately 624 ft below the production casing shoe, which is installed at a depth of 3,268 ft. This position provides a safe cement isolation distance for high-pressure injection tests.

4.2 Multi-Well Comparative Analysis (Shallow vs. Deep)

To test the hypothesis that depth negatively affects rock brittleness, the geomechanical profile of well 58-32 was compared with two deep wells: injection well 16A(78)-32 and monitoring well 78B-32. Both of these deep wells penetrated the main reservoir formation at depths $> 7,000$ ft.

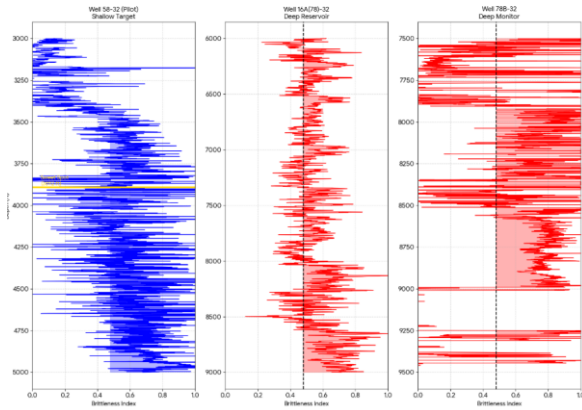


Fig. 4. Comparative fragility analysis in three wells based on the global baseline obtained from well 58-32. The shallow target in well 58-32 (blue line) shows a massive brittle interval, while the deep reservoir section in wells 16A and 78B (red line) is mostly ductile (BI < 0.48), which confirms the effect of containment on the rock failure mode.

The cross-section analysis in **Fig. 4** reveals a sharp contrast between the shallow and deep mechanical regimes:

1. **Shallow Regime (Wells 58-32):** Dominated by "blocky" intervals with consistently high BI. The histogram of the BI distribution shows a positive skew toward high values.
2. **Deep Regime (Wells 16A & 78B):** In the target reservoir interval (> 7,000 ft), the granitoid rocks show a drastic decrease in average BI values to 0.43–0.46.
 - Although Young's Modulus remains relatively high (~60 GPa), the increased Poisson's Ratio due to high confinement causes the rocks to behave more ductile (semi-ductile).
 - Zones with BI > 0.48 appear only as thin, discontinuous spikes, which most likely represent local mineralogical variations or drillhole artifacts, rather than massive fraccable zones.

Although well data from well 58-32 indicated high brittleness potential, physical confirmation was required to ensure that this zone was not simply a local anomaly. Therefore, validation was performed using spectral log data and drilling parameters from an offset injection well (16A) that penetrated the same stratigraphic interval.

4.3 Lateral Validation of Fracture Indicators

Due to the limited spectral log data in pilot well 58-32, validation of the presence of natural fractures was carried out using a lateral correlation approach (offset well analysis) in the nearest injector well, namely **Well 16A(78)-32**. These two wells have a close surface distance (<300 meters) with equivalent granitoid bedrock stratigraphy.

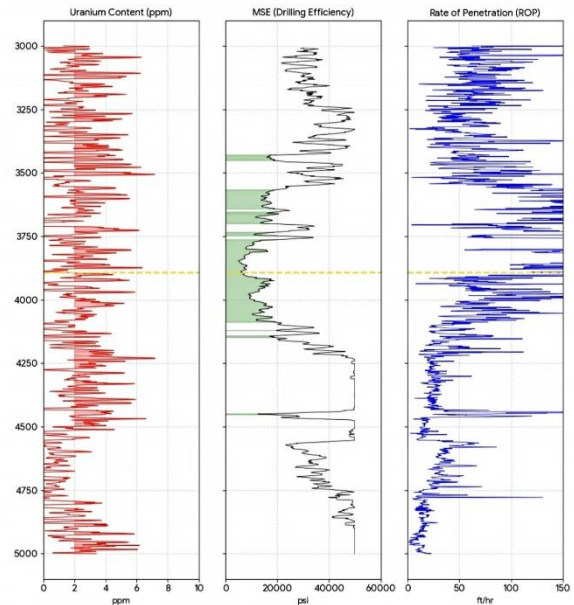


Fig. 5. Lateral validation of fracture indicators in offset well **16A(78)-32**. The correlation between spectral Uranium anomalies (> 3 ppm) and increased drilling efficiency (significant MSE decrease) at equivalent depths confirms the regional continuity of the permeable fracture zone.

As shown in **Fig. 5**, physical indicators of fractures are clearly recorded at depth intervals equivalent to the shallow target zone:

1. **Uranium Anomaly:** The Spectral Gamma Ray Log in well 16A recorded uranium concentrations reaching >3.0 ppm. In igneous formations, local uranium enrichment without an accompanying increase in thorium indicates secondary mineral precipitation in permeable fracture planes.
2. **Drilling Efficiency (MSE):** Mud log data shows a significant decrease in Mechanical Specific Energy (MSE) to below **20,000 psi**, which coincides with an increase in Rate of Penetration (ROP). This phenomenon, known as drilling break, confirms that the energy required to fracture the rock is drastically reduced due to the presence of a natural fracture network (pre-existing microfractures).

The consistency of these anomalous findings across two different wells strengthens the suspicion that the "Shallow Sweet Spot" is not merely a local feature, but rather a laterally extensive regional fracture zone, making it an ideal target for a DFIT (stimulation test).

The interpretation of uranium anomalies as a proxy for fractures should be done cautiously and should only be used as a supporting indicator, not the sole determinant.

5. Discussion

5.1 Geological Validation of the Sweet Spot (Data Triangulation)

The main finding of this study was the identification of a highly brittle granitoid rock interval at a depth of 3,892 ft in pilot well 58-32. However, a high Brittleness Index (BI) value alone does not guarantee successful stimulation if the rock is massive and without fissures.

The integration of multi-physics data in this study provides strong evidence for the presence of a **Permeable Fracture Corridor**:

1. **Mineralogical Evidence:** Uranium anomalies (>3 ppm) detected in an equivalent interval in well 16A indicate traces of ancient hydrothermal fluid flow. Uranium, in its oxidized state, dissolves in groundwater and tends to precipitate along open fracture planes during reduction (Keys, 1979). The absence of Thorium anomalies confirms that this signal does not originate from changes in clay lithology, but rather from purely secondary precipitation.
2. **Mechanical Evidence:** The drastic decrease in Mechanical Specific Energy (MSE) to <20,000 psi (Figure 5) proves that the drill bit penetrated a structurally "weak" zone. In hard, crystalline bedrock, such drilling breaks almost always correlate with a crushed zone or a high density of natural fractures.

The convergence of these three indicators (High BI + High Uranium + Low MSE) validates that the 3,892 ft target is an ideal candidate for stimulation: the matrix rock is stiff enough to hold proppant (high BI), yet already possesses natural "highways" (fractures) for fluid flow initiation.

5.2 Brittle-Ductile Transition Mechanism: Confinement Effect

One of the fundamental questions in the development of EGS at Utah FORGE is: "Why can the same granite rock be brittle in the shallow zone but ductile in the deep zone?"

The results of the comparative analysis (Fig. 5) answer this question through the principles of **Confining Stress Geomechanics**.

- In the shallow zone (~3,900 ft), overburden pressure and horizontal stress are relatively low, allowing the rock to maintain its elastic properties. When loaded, the rock tends to rupture explosively (brittle fracture).
- Conversely, in the deep reservoir (>7,000 ft) in wells 16A and 78B, the rock experiences a much higher effective confining stress (>40 MPa). According to the modified Mohr-Coulomb law of failure for deep rocks (Zoback, 2007), increasing

confining stress raises the shear failure threshold and facilitates plastic deformation before the rock actually ruptures.

According to the modified Mohr-Coulomb law of failure for deep rocks (Zoback, 2007), increasing confining stress raises the shear failure threshold and facilitates plastic deformation before the rock actually ruptures. The implications are fatal for EGS operations: Stimulation in this ductile zone carries a high risk of producing short, wide fractures that rapidly close when pump pressure is removed. Furthermore, at extreme reservoir depths, this brittle-to-ductile transition is effectively irreversible under in-situ conditions, fundamentally explaining why direct stimulation of the deep reservoir without prior calibration carries an inherently high risk of permanent hydraulic failure.

5.3 Strategic Implication: "Shallow Pilot Test" Proposal

Based on these geomechanical contrasts, this study proposes an operational paradigm shift through a **Gradual De-Risking strategy**. The 3,892 ft interval is proposed as the location for the **Diagnostic Injection Test (DFIT)** or Mini-Frac.

The strategic advantages of conducting pilot tests in this shallow zone include:

1. **Model Calibration:** Obtaining accurate in-situ breakdown pressure and leak-off coefficient parameters for calibrating the fracture simulator.
2. **Operational Risk Mitigation:** Testing the effectiveness of fracturing fluids and proppant in a more controlled environment (lower pump pressures) before applying them to the extreme deep zone.
3. **Cost Efficiency:** In the event of equipment failure or screen-out in the shallow zone, the cost of remediation (fishing/clean-out) is significantly lower than at depths of 8,000 ft.

A 30 ft thickness is sufficient for standard **Straddle Packer** installation with a 10-20 ft isolation interval, minimizing the risk of fluid bypass.

This approach offers a safer roadmap for commercial EGS development, where subsurface uncertainties are systematically reduced from shallow to deep zones.

6. Conclusion And Recommendations

6.1 Conclusion

Based on integrated petrophysical analysis and multi-well geomechanical characterization of the Utah FORGE field, the following conclusions can be drawn:

1. **Identification of a Shallow Mechanical Sweet Spot:** A discrete interval with superior geomechanical properties was identified in the Pilot Well 58-32 at depths of **3,892–3,922 ft**. This zone exhibits a highly brittle response (Brittleness Index > 0.82) and high formation stiffness (Young's Modulus > 75 GPa). The application of **robust P10-P90 statistical normalization** was critical in this identification, as it effectively filtered out borehole washout artifacts that otherwise masked the intrinsic rock quality, proving that standard normalization methods are insufficient for rugose boreholes in crystalline basements.
2. **Lateral Validation of Fracture Permeability:** The proposed target is confirmed to be a laterally extensive and permeable corridor, rather than a localized matrix anomaly. Evidence from the offset well 16A(78)-32 reveals **spectral uranium anomalies (> 3 ppm)**—geochemical fingerprints of paleo-fluid circulation—coinciding with a distinct **drilling break (MSE < 20 kpsi)**. This convergence of independent indicators provides high confidence that the zone contains pre-existing open fractures, which are essential for lowering breakdown pressure during hydraulic stimulation.
3. **Geomechanical Justification for De-Risking Strategy:** A sharp mechanical contrast exists between the shallow and deep granitoid sections. The deep reservoir (> 7,000 ft) is proven to behave in a **semi-ductile manner** (BI < 0.46) dominated by high confinement stress (> 40 MPa), which suppresses fracture complexity. Conversely, the identified shallow sweet spot retains favorable brittle behavior. Therefore, this study concludes that executing a **Diagnostic Fracture Injection Test (DFIT)** in the shallow interval is a scientifically justified strategy to calibrate fluid designs and proppant transport models with significantly lower operational risk before targeting the semi-ductile deep basement.

6.2 Recommendations

For further research and operational development, it is recommended that:

1. Collect **Formation Micro-Imager (FMI)** or **Ultrasonic Borehole Imager (UBI)** data at 3,800–4,000 ft intervals during subsequent well drilling to directly visualize fracture orientation and aperture.
2. Conduct 3D numerical simulations (**Hydraulic Fracture Modeling**) using the

geomechanical parameters calculated in this study to predict the fracture geometry that will form in the shallow target zone.

References

- Allis, R., Gwynn, M., Hardwick, C., Hurlbut, W., Kirby, S. M., & Moore, J. N. 2019. Thermal characteristics of the Roosevelt Hot Springs system, with focus on the FORGE EGS site, Milford, Utah. *Utah Geological Survey Miscellaneous Publication*, 169, 1–20.
- Allis, R., Moore, J., McLennan, J., Kirby, S., & Hardwick, C. 2016. EGS Concept Testing and Development at the Milford, Utah FORGE Site. *Proceedings of the 41st Workshop on Geothermal Reservoir Engineering*, Stanford University.
- Keys, W. S. (1979). Borehole geophysics in igneous and metamorphic rocks. *Society of Professional Well Log Analysts (SPWLA) Reprint Volume*, Tulsa, Oklahoma.
- Moore, J., McLennan, J., Allis, R., et al. 2019. The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): A Status Report. *Proceedings of the 44th Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-214.
- Nielson, D. L., Moore, J. N., & Hulen, J. B. 2017. Geology of the Mineral Mountains Intrusive Complex, Utah. *Geothermal Resources Council Transactions*, 41, 280–292.
- Perez, R., & Marfurt, K. 2014. Mineralogy-based brittleness prediction from surface seismic data: Application to the Barnett Shale. *Interpretation*, 2(4), T255–T271. <https://doi.org/10.1190/INT-2014-0036.1>
- Rickman, R., Mullen, M. J., Petre, J. E., Grieser, W. V., & Kundert, D. 2008. A practical use of shale petrophysics for stimulation design optimization: All shale plays are not clones of the Barnett Shale. *SPE Annual Technical Conference and Exhibition*, SPE-115258-MS.
- Teale, R. 1965. The concept of specific energy in rock drilling. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 2(1), 57–73.
- Wang, Y. K., & Stewart, R. R. 2024. Subsurface Imaging by a Post-Stimulation Walkaway Vertical Seismic Profile Using Distributed

Acoustic Sensing at the Utah FORGE
Enhanced Geothermal System Site.
Energies, 17(13), 3119.
<https://doi.org/10.3390/en17133119>

Xing, P., Yoshioka, K., Adachi, J., & Elsworth, D.
(2020). Lattice Boltzmann simulation of
fluid flow in fracture networks:
Applications to EGS at Utah FORGE.
Geothermics, 87, 101833.

Zoback, M. D. (2007). *Reservoir Geomechanics*.
Cambridge University Press.
