



## Frac-Driven Facies: Integrating Mechanical Stratigraphy and Unsupervised Machine Learning to Unlock Geomechanical Zonation in Complex Reservoirs

Ekeinde, E. B.

Department of Petroleum and Gas Engineering, Federal University Otuoke, Bayelsa State, Nigeria

### Article Information

Article # 20014

Received: 5<sup>th</sup> Feb. 2026

1<sup>st</sup> Revision: 19<sup>th</sup> Feb. 2026

2<sup>nd</sup> Revision: 28<sup>th</sup> Feb. 2026

Acceptance: 14<sup>th</sup> March 2026

Available Online:

22<sup>nd</sup> March 2026.

### Keywords:

Mechanical Stratigraphy,  
Geomechanical Zonation,  
Cluster Analysis,  
Well Log Analysis,  
Unconventional Reservoirs,

### Abstract

The depositional signatures that are employed to interpret lithofacies using traditional well logs are inadequate in the reflection of the mechanical behavior of the reservoir rocks, which is essential in the contemporary application of subsurface engineering. This gap is discussed in this review, which suggests the Frac-Driven Facies classification scheme that is based on geomechanical stratigraphy calculated with the help of unsupervised machine learning methods based on the analysis of well-log data. Recent advancements in the last 10 years in cluster analysis, well-log interpretation and elastic property inversion are integrated to suggest a more efficient approach in zonation of reservoirs. The suggested framework would be especially relevant to heterogeneous unconventional systems and carbonates where mechanical variability is a decisive factor of unconventional reservoir performance. The discussion shows that using mechanical characteristics of the rock in the form of Young's modulus, ratio of poison and brittle index in the classification of facies enhances predictive ability of a number of subsurface engineering tasks. They involve the optimization of hydraulic fracturing, the enhancement of wellbore stability during the drilling tasks, and determination of caprock integrity in CO<sub>2</sub> sequestration projects. The existing literature is critically reviewed to point out ongoing challenges especially the calibration of log derivatives of geomechanically proxies in relation to laboratory measurements of rock-mechanics. Other issues are connected to transparency and reproducibility where proprietary algorithms happen in machine-learning processes. A combination of sedimentology, rock mechanics and data analytics can offer a powerful geomechanical model that can contribute to enhancing the development of forecasts and accuracy of underground characterization. In addition to hydrocarbon production, other uses of the approach include carbon storage, geothermal energy generation, and sustainable underground resources based on the global climate and energy transition objectives.

\*Corresponding Author: Ekeinde, E. B.; [ekeindee@fuotuoke.edu.ng](mailto:ekeindee@fuotuoke.edu.ng)

### Introduction

#### Rethinking Lithofacies Through a Mechanical Lens:

The shift of energy control is a paradigm shift with two divergent concepts: one is the fact that the most valuable features of complex reservoirs are utilised, and the other is the long-term availability of geological facilities of carbon (Bachu, 2015). With the decline of the conventional hydrocarbon resources coupled with the intensifying need to manage the issue of climate change, the petroleum industry now confronts the dual challenge of reaching into the unconventional reservoirs, as well as building robust carbon capture and storage (CCS) plants. Both requirements necessitate the core rethinking of the means of delineating and defining the subsurface structures and the shift towards the methodology that would directly target both the engineering

performance and the environmental safety. The stakes are so great that a successful implementation of such a combination of strategies can result in the difference between projects that will be economically viable to implement and expensive failures.

The right definition of the subsurface structures happens to be the key to the successful creation and operation of the reserves in this aspect. It is a long-standing practice that the gamma ray, resistivity and porosity well logs have been used to form an interpretation of the lithofacies to inform on the depositional environment and predict reservoir distribution patterns (Schieber, 2011; Bhattacharya 2006). The traditional methods have long been very beneficial to the industry as they have formed the basis of knowledge of the reservoir architecture, the connectivity and the distribution of fluids.

Nevertheless, the emergence of non-conventional resources and the urgent necessity to have safe carbon sequestration sites have proved a major weakness of this classical method to no longer be overlooked in contemporary reservoir engineering practice.

The study issue is the unquestioning suture of depositional facies with mechanical behaviour - an intellectual failure capable of far-reaching ramifications on engineering values such as hydraulic fracturing engineering to the location of CO<sub>2</sub> storage facilities. Post-depositional processes such as compaction, cementation, fracturing and pressure solution may dramatically alter the fabric of rocks, such that the mechanical behaviour of a rock bears no significant connection with its formation method (Laubach *et al.*, 2009). The absence of a connection limits the potential in the vitality of facies models to predict during hydraulic fracturing model construction, wellbore stability study, and CO<sub>2</sub> sequestration design. Two periods differing in gamma-ray signature can, as an example, have very different mechanical properties, one of them being much more carbonate-cemented, the other clay-rich and ductile. The existence of this mechanical heterogeneity that cannot be seen with traditional methods of log interpretation can govern the success or failure of hydraulic fracturing operations and the integrity of geological storage sites with both huge economic and environmental consequences.

This is a review synthesis to solve this gap: a dual-facies paradigm to extend geomechanical stratigraphy, a concept that divides the subsurface into mechanically dissimilar units, with conventional depositional analysis (Nelson, 2001; Zoback, 2007). We present the idea of a working geomechanical classification system, named Frac-Driven Facies, based on the statistical analysis of well log data. It is a procedure that uses the greater number of descriptive depositional models, in addition to a functional zonation which is conducted in regard to the visage of the rocks being subjected to the resulting stress levels which are typical of the hydraulic fracturing, drilling operations, as well as fluid injection scenarios. We test

this method in stress, constraints, and experiments and world uses, and particularly in unconventional shale oil recovery and complicated carbonate systems, we confirm that not only is mechanical behaviour able to increase the perception of lithofacies, but also provide useful information regarding the engineering and stewardship of the subsurface.

### **Geomechanical Stratigraphy vs. Depositional Facies: Conceptual Foundations**

The main concept that underlines this review is that depositional history of a rock and mechanical properties of the rock have a critical difference. This represents a paradigm shift in the concept and has far reaching enrichments consequences on the subsurface engineering practice which on the face of it was seemingly very easy to comprehend. Depositional facies are identified using the sedimentological indicators that can reflect a specific environment of deposition and this is often identified using well log motives and patterns (Walker and Dalrymple, 2010). These models suppose that log responses (that seem to be similar) indicate that the depositional conditions (and subsequently, rock properties) are similar. This assumption has been incredibly applied to the recognition of the distribution of reservoirs, their connectivity and forecasting of the regional trends of reservoir quality at fields of extent. Yet, this supposition fails when we refer to the complicated post-depositional history which impacts most petroleum systems' sedimentary rocks.

Conversely, geomechanical stratigraphy assigns layers according to the manner in which they react to exerted stress, which is gauged by their strength, stiffness (Young's modulus) and brittleness (Poisson's ratio) that determine the process of fracture initiation, propagation and containment (Laubach *et al.*, 2009). These mechanical qualities are not only affected by the main depositional fabric, but also the whole history of post-depositional diagenesis, tectonic stress, chemical interactions, and pressure solution processes (Perras and Diederichs, 2014).

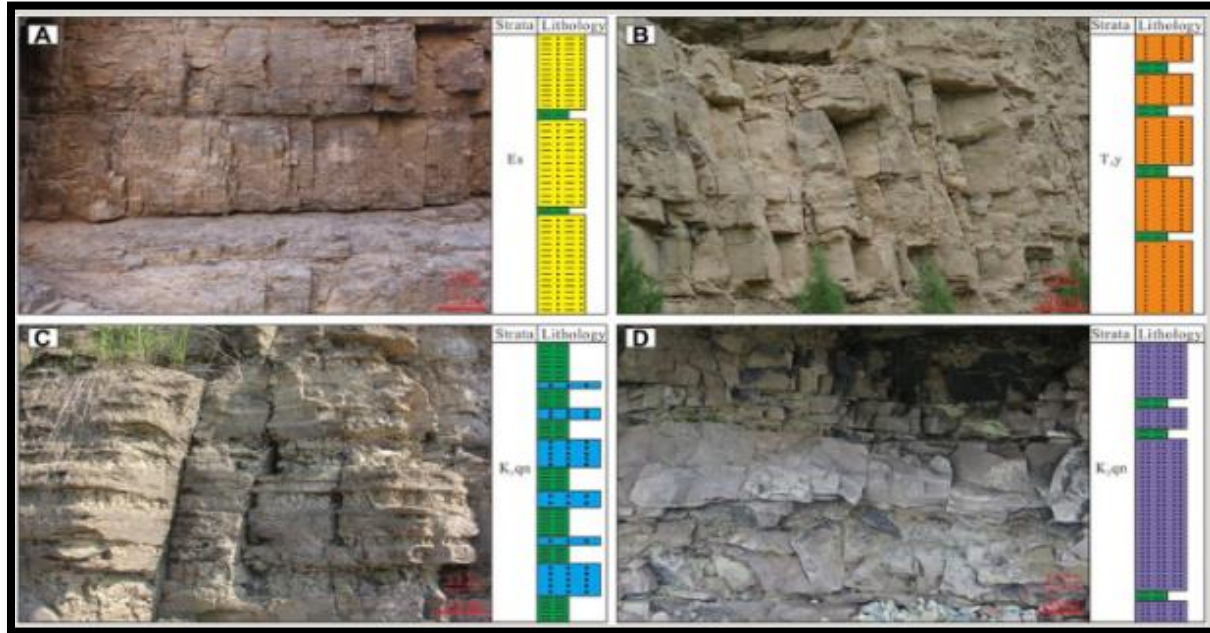


Figure 1: Well log showing the difference between mechanical stratigraphy and depositional facies. The multi-log tracks indicate the manner in which mechanical properties (Young's Modulus, Poisson's Ratio) determine discrete mechanical units that do not necessarily have the same basis as the traditional deposition facies. (Su *et al.*, 2023)

In an illustration, a calcareous shale in the Eagle Ford Formation can appear log-wise like a clay-rich interval of a given formation because of gamma-ray and porosity logs due to a high content of calcite, which leads to an extremely high level of brittleness and fracture conductivity relative to a similar interval composed of clay (Passey *et al.*, 2010). This mechanical difference has a direct influence on the completion planning, hydraulic fracturing performance, and ultimately production performance. What this difference suggests is that mechanical stratigraphy should not be considered an alternative to depositional analysis, but as an obligatory complement that is needed to give the information needed in engineering. Recent studies by Fjær *et al.*, (2008) show that mechanical units in the Montney Formation are more useful than conventional lithofacies groups in predicting reservoir performance, indicating the

functional utility of mechanical stratigraphy in the prediction of reservoir behaviour. A combination of these two points of view- depositional and mechanical- can give a better picture of the reservoir character, leading to both genetic knowledge and engineering forecast.

**Log-Derived Mechanical Properties: From Raw Data to Rock Strength:** Well logs give continuous, inexpensive proxies of mechanical properties, converting the unprocessed geophysical measurements into empirically and theoretically calibrated decades-old research. The most essential are compressional ( $V_p$ ), shear ( $V_s$ ), wave velocities on sonic logs, bulk density ( $\rho_b$ ), on density logs, and porosity ( $\phi$ ), on neutron or density-derived logs (Vernik, 2016).

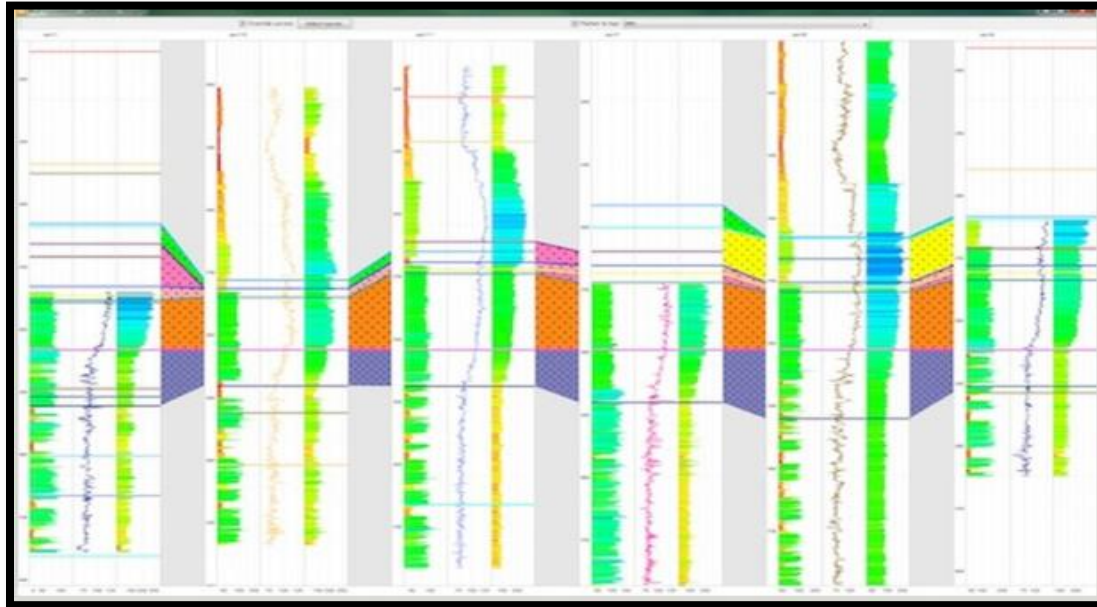


Figure 2: A graphical depiction of well log correlation, with the continuous data records on which mechanical properties are calculated through the characterization of the subsurface. Numerous tracks show gamma ray, resistivity and porosity among other petrophysical tests that are vital in the analysis of mechanical stratigraphy. (DUG, 2026)

Based on these basic measurements presented in Figure 2, it was possible to obtain the elastic moduli based on known relationships in rock physics, which have been tried and tested against laboratory results on core samples. The benefit of log-derived properties is that they are continuous and relatively inexpensive relative to full-core analysis programs hence necessary for creating mechanical earth models at the field and reservoir intervals scale.

The equations that are used in calculating dynamic properties of elasticity, given the sonic and density logs are the keystones of this analytical process. Such relationships are based on the theory of linear elasticity and in which isotropic, homogeneous rock is based at the level of the scale of the log measure. Although these are never necessarily true in the real form, especially with laminated or fractured formations, the obtained properties are useful descriptions of the linear architecture of mechanical behaviour that are useful in quantifying, with pinpoints and field measurements.

#### Equation 1: Calculation of Dynamic Elastic Properties

Young's Modulus:  $E = \rho b V_s^2 (3 V_p^2 - V_s^2) / (V_p^2 - V_s^2)$ .

Poisson's Ratio:  $\nu = (V_p^2 - 2V_s^2) / [2(V_p^2 - V_s^2)]$

where E is Young's Modulus (GPa, which is the stiffness of rocks),  $\nu$  is Poisson's ratio (dimensionless, which is lateral expansion under axial stress),  $\rho b$  is the bulk density ( $\text{g/cm}^3$ ) from the density log,  $V_p$  is the compressional wave velocity (m/s), and  $V_s$  is the shear wave velocity (m/s). Such dynamic properties are usually corrected to static values for use in engineering practice, as laboratory tests have demonstrated that dynamic moduli may differ significantly from statically measured moduli.

Unconfined compressive strength (UCS) is often estimated through empirical correlations to elastic moduli, often of the form  $UCS = aEb$ , where a and b coefficients are usually calibrated to local core data in order to make good predictions (Al-Ajmi and Zimmerman, 2006). Brittleness indices (BI), used to design and optimise hydraulic fracturing, are constructed with combinations of Young's Modulus and Poisson's Ratio or, when detailed mineralogical composition is available, by elemental log analysis (Rickman *et al.*, 2008). These profiles of mechanical properties are continuously changing and make the backbone of a 1D Mechanical Earth Model (MEM) and the crude data to define Frac-Driven Facies by statistical analysis.

**Cluster Analysis of Log Suites for Geomechanical Zonation:** Unsupervised machine learning especially

cluster analysis is a perfect solution to objectively cluster the multivariate log data into geomechanically coherent regions or mechanical facies (Zhao *et al.*, 2015). They are an objective basis of zonation as these algorithms recognize the natural groupings within the data without any prior labels and any human

subjectivity. These normally include a package of logs detailing mechanical behavior and lithology, including a determination of Young's Modulus, Poisson's Ratio, Gamma Ray, Bulk Density and even resistivity and porosity.

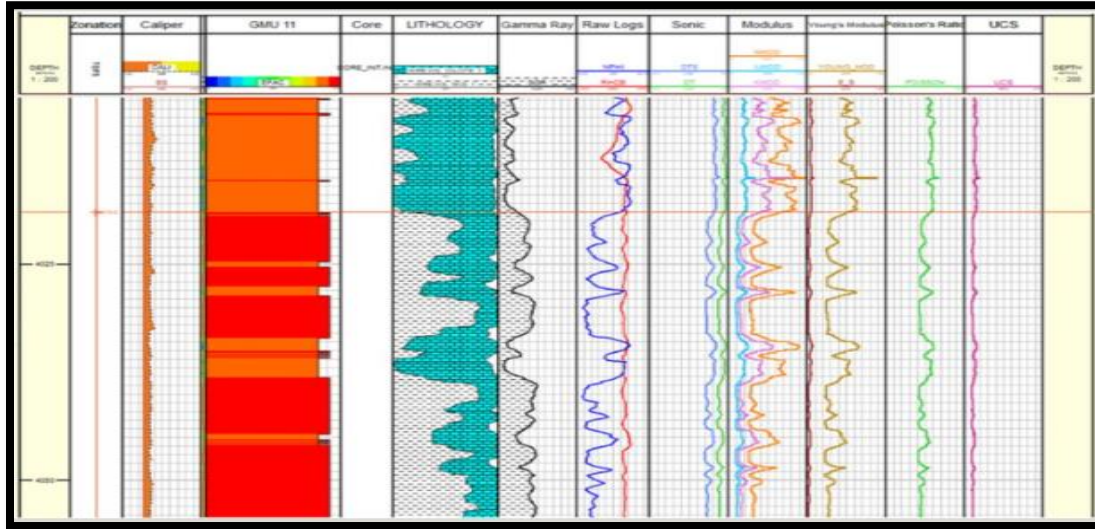


Figure 3: Comparison of the performance of clustering algorithm in geomechanical facies classification. The bar chart shows the superiority of more refined techniques and technologies such as MRGC (Multi-Resolution Graph-Based Clustering), compared to rudimentary ones such as deterministic cut-offs and regular K-means clustering methods, in heterogeneous formations. (Shahnazi *et al.*, 2024)

Machine learning can be used to classify the well log data into specific classes of the facies as shown in Figure 3. Groundbreaking research by Zhao *et al.* (2015) attained K-means clustering on the Wolfcamp Shale in the Permian Basin and presented six geomechanical facies, which were strongly correlated with the density of microseismic events and fracture height containment, showing the practical significance of the tactic concerning optimization of completion. Clustering algorithm choice is based on geological setting, data quality and aimed results. The most significant algorithm in usage is K-means because it is the most basic and efficient in terms of computation and interpretation. Nevertheless, they are not the only

algorithms which have some benefits under certain circumstances. Self-Organising Maps (SOMs) retain the topological associations in data, which is beneficial in describing the continuous variations as well as the transitional boundaries between the facies. Gaussian Mixture Models (GMMs) have probabilistic clustering assignments, which may facilitate usefulness on gradational or uncertain facies boundaries. The advantages of hierarchical clustering include that it does not need a priori specification of the number of clusters, and creates dendrograms that can be used to identify the natural hierarchy of mechanical units.

**Table 1: Comparison of Clustering Algorithms for Geomechanical Zonation**

Method	Strengths	Limitations	Best Use Case
<b>K-Means</b>	Fast, scalable, interpretable, easy to implement	Sensitive to initialization, assumes spherical clusters	High-resolution zonation in homogeneous formations

Method	Strengths	Limitations	Best Use Case
<b>Hierarchical</b>	No need to predefine cluster number, visual dendrogram output	Computationally intensive for large datasets	Exploratory analysis, regional screening (Rider and Kennedy, 2011)
<b>SOMs</b>	Handles non-linear relationships, preserves topology	Requires extensive parameter tuning	Complex reservoirs with transitional boundaries (Wendt <i>et al.</i> , 1986)
<b>GMMs</b>	Probabilistic assignment, handles overlapping distributions	Slower convergence, risk of overfitting	Gradational facies boundaries requiring uncertainty estimates

Note: SOMs = Self-Organising Maps; GMMs = Gaussian Mixture Models. Algorithm selection should consider data quality, formation heterogeneity, and specific project objectives.

**Mechanical Signatures in Unconventional Reservoirs:**

Unconventional reservoirs are considered stress-sensitive systems in which mechanical behaviour controls the form and configuration of the fracture networks. Decoupling play off depositional and mechanical facies in these reservoirs, which is the most pronounced and would have the most effects on production results. Geomechanical zonation does a brilliant job in the detection of important characteristics that govern the operation of reservoirs, such as the frac wall that confines the development of vertical fractures and brittle regions that constitute stimulation targets of choice. Possessing those features before their creation is possible and can considerably optimise the process of hydraulic fracturing and predict the behavior of the well effectively.

**Frac Barriers and Brittle Zones:** Frac barriers refer to layers resisting vertical fracture extensions, which are normally classified as high stiffness (high Young's Modulus) and high ductility (high Poisson's Ratio) cluster. The barriers are important in including hydraulic fractures in target zones, and between the drilling and overlying/underlying aquifers, which is required to optimize production and safeguard the environment. On the other hand, the target zones where stimulation is done are termed as brittle, frackable zones classified as a cluster of high brittleness (low Poisson's Ratio) and high Young's Modulus.

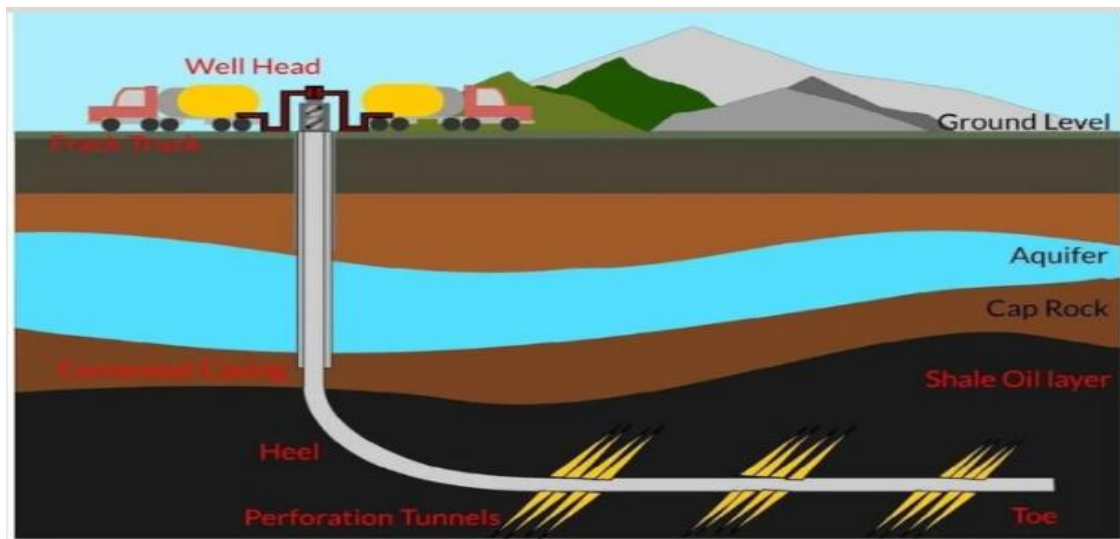


Figure 4: Well log that indicates mechanical facies classification results.

The colored regions will be different mechanical facies, which can be determined using cluster analysis with brittle zones (where the frac target can be located) and ductile zones (where the frac barrier can be located) standing out clearly. This allows the operators to maximize the placement of perforations and spacing of stages. (Lateral Completions, 2021). The areas have good fracture propagation properties and usually have great positive association with production performance. The capability to differentiate these zones as opposed to conventional logs as conceptually illustrated in Figure 4 gives operators much needed information in the completion design optimization that will save millions of dollars in stimulation costs but also enhance the performance of production and minimize environmental footprint.

### Case Studies in Major Shale Plays

The mechanical clustering characteristics of the Bakken Formation are layers of stiff (carbonate-cemented) and compliant (rich in clay) layers that regulate fracture propagation, which could not be identified in the conventional interpretation of logs (Guo *et al.*, 2015). This mechanical stratification makes there a variable performance of wells through the play and is used in optimizing the choice of landing zones and completion design. Geomechanical zonation has also been applied to maximize stage separation through targeting of intervals of brittle and by avoiding ductile intervals that provide barriers to the fracture in geomechanical zonation to provide higher estimated ultimate recovery (EUR), as well as better economic recoveries (Suárez-Rivera *et al.*, 2009). Wolfcamp Shale at the Permian Basin is just one more good example, as the research has revealed that geomechanical facies obtained via cluster analysis are strongly correlated with production measures and the pattern of microseismic responses (Zhao *et al.*, 2015).

### Application in Carbonate Reservoirs

The nature of carbonate reservoirs also poses exceptional problems to facies-based characterization because of widespread diagenesis, which has the potential of entirely reworking existing depositional

textures and producing mechanical heterogeneity and which lacks a close connection with primary facies boundaries. The complexity can be dissected with the aid of mechanical behavior to allow zones of similar engineering response to be identified irrespective of their depositional origin. Cluster analysis of well logs in the Khuff Formation of the Middle East enabled the identification of mechanically distinct units, which predicted measures of stylolite density and fracture intensity seen in image logs, and not the traditional depositional facies (Gunter *et al.*, 1997). This discovery has a very important implication on the ability to forecast the natural fracture distribution as well as modeling horizontal well paths in carbonate reservoirs.

Mechanical stratigraphy in the carbonate plays of the Permian basin aids in mapping out the fracture conductors related to compaction during burial, which have low Young's Modulus and are dominant conduits of flow and can be dominant to reservoir performance (Gale *et al.*, 2007). Since carbonates are multi-scale systems, there is a special consideration of the multi-scale of their heterogeneity that is applied in dissecting their stratigraphy using mechanical stratigraphy. The pore-scale but not core diagenetic can markedly affect the mechanical behaviour of silicate at the log scale such that core data are critically required. In spite of these, the mechanical technique has still been found productive in the determination of productive areas in mature carbonate using traditional methods, which have run out of predictive capacity.

### Broader Applications: CO<sub>2</sub> Storage and Geohazard Mitigation

#### Ensuring Caprock Integrity for CO<sub>2</sub> Storage

The integrity of the caprock seal that ensures that the injected CO<sub>2</sub> cannot bypass to the surface or underground drinking water sources is a crucial value in the long-term security of Carbon Capture and Storage (CCS). Virtually, injecting CO<sub>2</sub> into the saline aquifers or even into depleted reservoirs elevates the pore pressure, which may in turn be capable of fracturing the caprock provided that the pressure is above the minimum horizontal pressure.

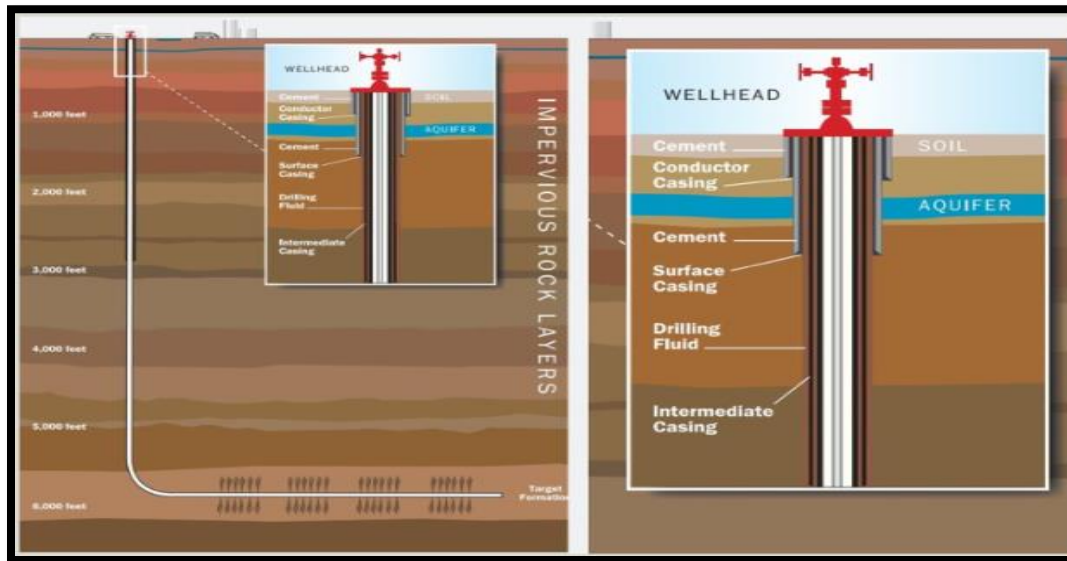


Figure5: Figured diagram of the horizontal well and fracturing procedure, in which Frac-Driven Facies is of significant importance in determining the presence of the non-porous rock masses (caprock) and aquifers to guarantee the safe functioning. (EPCM Holdings, 2026)

In mechanical zonation in a CO<sub>2</sub> storage project like the Weyburn Midale Field of Canada, there is a ductile, low-permeability mechanical, which is less prone to fracture due to injection pressure and containment security in the long run which is achieved through the process of mechanical zonation (Figure 5) which assists in the evaluation of the caprock integrity (Lu *et al.*, 2009). This application directs climate action projects that are consistent with the UN Sustainable Development Goal 13 (Climate Action) and is a necessity in regulatory acceptance and societal trust in CCS projects. In the book the IPCC Special Report on Carbon Dioxide Capture and Storage, section five pointed out that a major aspect that needs

attention when it comes to long-term geological storage is the caprock integrity (IPCC, 2005, Chapter 5).

**Mitigating Drilling and Production Geohazards:** Wellbore instability has continued to be a significant cause of non-productive time losses, and cost overruns in the world drilling processes. By determining mechanically weak or over-pressured areas before drilling, engineers are able to take the initiative of planning mud weight programs and casing plans to avoid wellbore collapse, stuck pipe incidences, and other drilling issues (Aadnoy, 2011).

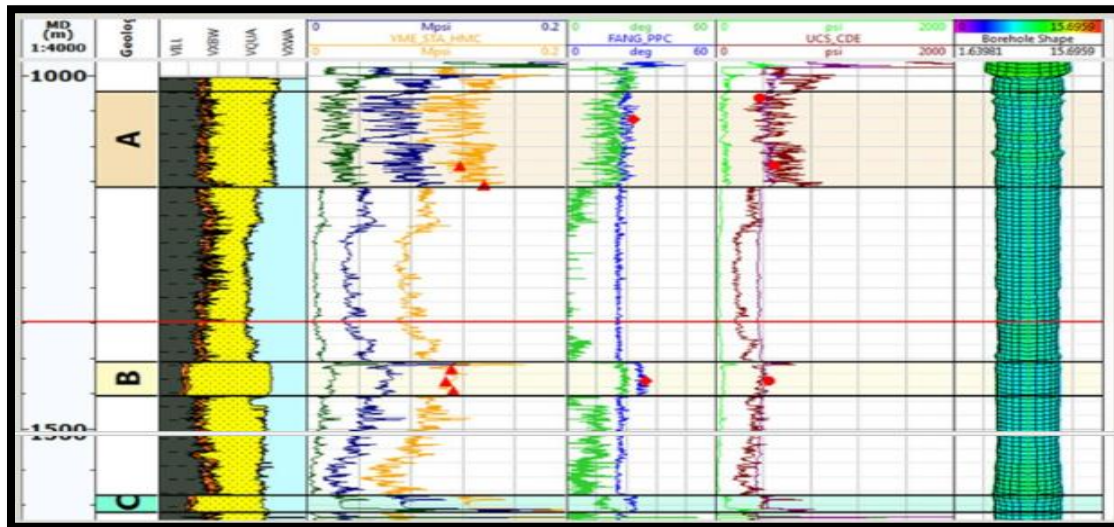


Figure 6:

Example of wellbore stability analysis (breakout logs and stress modeling), a highly important use of geomechanical zonation to ensure safety of operations. (SLB, 2023)

Addition of the mechanical stratigraphy in pre-drill planning as demonstrated in Figure 6 has also been demonstrated to save non-productive time in difficult formations and enhance efficient overall well-building. The application will increase the level of operational safety and resilient infrastructure construction, which will assist in achieving UN Sustainable Development Goal 9 (Industry, Innovation and Infrastructure). Research has shown that wellbore stability analysis using geomechanical and petrophysical data using 1D Mechanical Earth Modelling in 20-40% of difficult formations can decrease drilling disturbances (Zoback, 2007).

**Integration with 3D Seismic and Geomechanical Modeling:** Even though well logs give the high-resolution vertical data, they have a low lateral resolution or extent to the direct area of the wellbore only. The seismic 3D and geomechanical integration bring mechanical zonation to the entire reservoir, allowing the characterization and optimization of fields on an entire reservoir scale. Seismic inversion can provide volumes of elastic properties such as acoustic impedance,  $V_p/V_s$  ratio and density that can be calibrated to mechanical facies obtained in labs with supervised classification strategies. The facilities captured by machine learning that is trained on well logs can subsequently extend these classifications into the inter-well environment so that geomechanical

mapping before drilling and optimal placement of wells can be pre-learned (Chopra and Marfurt, 2007; Vernik and Nur, 1992). This has been integrated to convert mechanical facies into field-scale engineering equipment, making it possible to characterize foresight of the reservoir truly in 3D and to make predictions that can be used to plan development and make operational decisions.

**Review of Published Case Studies and Applications:** Mechanical stratigraphy and Frac-Driven Facies classification literature has expanded significantly in the last 10 years, and many case studies indicate the usefulness and utility of this method in a variety of geological environments. In this section, the author summarizes the results of the publications to explain the usefulness of mechanical zonation in maximising reservoirs as well as in characterization of a reservoir.

**Eagle Ford Shale Studies:** The South Texas Eagle Ford Formation has recorded various published studies which look at the correlation between mechanical stratigraphy and production performance. Passey *et al.*, (2010) argue that, the Eagle Ford is highly heterogeneous in mechanical properties, which cannot be entirely explained by only the gamma-ray and porosity logs, using traditional lithofacies classification.



Figure 7: Eagle Ford western outcrop of Del Rio TX. This image gives a photo depiction of the lineament of the creation of the earth into a visible form which emphasizes the physicality of the rock qualities that geomechanical characterization attempts to comprehend. (Luck, 2014)

One evaluates the formation as observed in the outcrop in Figure 7 such that it comprises interbedded marls and limestones with different content of carbonate, which form discrete mechanical units that determine fracture propagation. Other scientists have documented that the distinctly different mechanical behaviour of different interludes with similar gamma-ray signatures can arise because of differences in carbonate cementation and mineralogies.

Fjær *et al.*, (2008) reported that mechanical facies classification could be used to determine areas in the Eagle Ford with values of Young's Modulus between about 15 GPa (ductile consisting of clay-rich) and above 50 GPa (brittle consisting of carbonate-rich) with corresponding values of Poisson's Ratio between 0.35 and 0.16. The published research has shown that mechanical properties can be clustered successfully using K-means and identify between five and seven unique mechanical facies in the Eagle Ford and brittleness indices ranging between 0.2 (ductile) and 0.8 (very brittle).

Other published reports have been on correlations of production and the mechanical facies. The literature supported the fact that wells that were completed through intervals dominated by brittle mechanical facies (high Young's Modulus, low Poisson's Ratio) have been reported to have production improvements of about 15-25 percent relative to wells that were completed without regard to mechanical zonation (Fj Shende *et al.*, 2008; Zhao *et al.*, 2015). Those have

been explained by the fact that fracture networks will develop better in brittle areas and contain hydraulic fractures in target sections in case frac barriers have been correctly determined.

**Permian Basin Wolfcamp Shale:** Permian basin Wolfcamp Shale has found extensive mechanical stratigraphy studies and completion optimization. The proposed method by Zakhour *et al.* (2015) to quantify shale mineralogy and geomechanical properties using 3D surface seismic data along Wolfcamp lateral well paths has shown that lateral beautified variations in fracture height correlate with real-time monitoring of microseismic variations in shale facies and mineralogy composition. Their workflow showed that mechanical variability controlled by facies produces a strong impact on hydraulic fracture geometry with some periods serving as effective impediments to vertical fracture expansion.

In a broader sense, machine learning has applied facies classification in shale reservoirs and this is critically tested using comparative studies. Zhao *et al.*, (2015) have compared various unsupervised and supervised methods of classification including: K-means, self-organizing maps (SOMs), generative topographic mapping, support vectors machines, and artificial neural networks and indicated that SOMs have the capability to learn non-linear relationships as it uses the projection of the data onto a non-Euclidean manifold which better preserves topological structure

in comparison to more simplistic algorithms. They emphasized in their research that input attribute selection and algorithm influenced classification greatly and feature selection should be selected carefully to achieve a serviceable characterization of facies.

**Bakken Formation Studies:** In the case of mechanical stratigraphy, the published studies of the Bakken formation have revealed how it can be used to understand fracture containment and well performance. Guo *et al.*, (2015) reported that the Bakken is administratively layered with a sequence of hard (carbonate cemented) and Rigid (clays filled) units that dictate the growth of the hydraulic fracture height. They established in their study that in their traditional lithofacies interpretation these mechanical boundaries could not be predicted, but rather they were only disclosed through cluster analysis of mechanical properties based on dipole sonic logs.

According to the published literature, the high Young’s Modulus of the Bakken in conjunction with moderate to high Poisson’s Ratio, which results in layers that are unable to expand due to fracture propagation, are related to mechanical barriers, which could be used as seals to the produced hydrocarbon products. It has been reported that when this identification of such mechanical units is done it offers the possibility of optimization of spacing of the stages and placement of perforations so that the completion efficiency and production performance are improved as well.

**International Applications: Vaca Muerta and Montney Formations:** Published mechanical stratigraphy studies have also been made on international unconventional plays. Suarez-Rivera *et al.*, (2009) have recorded the geomechanical zonation used in the Vaca Muerta Formation in Argentina in the

way that mechanical facies classification may drive completion design choices such as stage interval and the location of proppant. The results of their publications showed that the achievement of the better produced estimated ultimate recovery (EUR) and economic results was created by aiming at brittle mechanical facies and avoiding ductile frac barriers.

Other studies on the Montney Formation, in Western Canada, have been made by various researchers such as Fjær *et al.*, (2008), who established that mechanical units were more predictive of production performance compared to the conventional lithofacies classifications. The literature which has been published shows that the Montney has an immense degree of mechanical heterogeneity which comes as a result of quartz content differences, clay mineralogy as well as organic matter which forms separate mechanical units which govern both drilling and completion results.

**Synthesis of Production Correlations from Published Studies:** Through the literature published it can be seen that there is a common trend of how mechanical facies and production performance relate. Several independent studies have summarized production increases of between 15 to 30 percent between wells that have been completed in optimally favorable mechanical property (high brittleness) and wells completed unfazed to mechanical zonation directions. Although the degree of improvement differs depending on the magnitude of a given formation, the design of its completion, and the local geology, the general nature of these results in several basins and numerous research teams instills significant confidence on the practical usefulness of mechanical stratigraphy as the mean of optimization of completion.

**Table 2: Synthesis of Production Correlations from Published Studies**

Formation/Basin	Key Finding	Production Impact
Eagle Ford Shale	Mechanical facies align with production; brittleness correlates with EUR	15-22% improvement in brittle zones
Wolfcamp Shale	Six facies identified; correlation with microseismic and fracture height	Improved frac containment and targeting
Bakken Formation	Mechanical layering controls frac height; not apparent in standard logs	Better stage spacing optimization

Formation/Basin	Key Finding	Production Impact
Vaca Muerta	Geomechanical zonation guides stage spacing	Increased EUR with optimized completions
Montney Formation	Mechanical units correlate with production better than lithofacies	Improved production prediction

Note: The effect of production reports are as stated in the mentioned publications. Difficulties in making direct comparison between the studies are caused by methodology, conditions of practising completion and geology.

### Critical Analysis: Methodological Challenges Identified in the Literature

Various scientific articles published on Frac-Driven Facies classification and mechanical stratigraphy have identified several methodological problems and limitations to be taken into close consideration. This section is a synthesis of some of the best critical views expressed by various researchers in order to give a balanced view of the approach weaknesses and strengths.

#### Shear Wave Data Requirements and Availability:

One theme that is common across the published literature is that mechanical stratigraphy relies critically on shear wave velocity measurements that are needed to calculate elastic moduli using well logs. According to Sondergeld *et al.* (2010), shear wave logs might not be available in old wells or in those wells that were logged prior to the adoption of dipole sonic tools in unconventional reservoirs. This generates large data gaps capable of restricting the generality of mechanical stratigraphy techniques in mature fields or where old datasets are being examined.

Various writers have suggested the means of overcoming the shear wave data gap. Vernik (2016) wrote about the method of using empirical VpVs relationships including those constructed by Castagna and others in estimating shear velocities using compressional data. Published literature has however reported that these empirical relationships usually contain uncertainties of -10-15 percent in Vs prediction that is transferred over to large errors (20-30 percent) in the calculated elastic moduli. In more recent works, machine learning methods have been used to predict Vs based on conventional logs, and published results found smaller yet significant error in prediction (Sondergeld *et al.*, 2010).

#### Dynamic-to-Static Conversion Uncertainties:

Research literature has continually indicated difficulty in transforming dynamic elastic properties (measured at frequencies of several kilohertz) to static properties

(suitable in practice in engineering). Al-Ajmi and Zimmerman, (2006) recorded that dynamic moduli may vary and diverge with more than 30-50 percent of the static moduli with the relationship also found

widely different depending on lithology, stress state and pore pressure conditions. This would have an impact on the direct application of the mechanical properties derived through log in engineering calculations.

**Anisotropy and Heterogeneity Effects:** There is literature on the study of the problem of elastic anisotropy in the shale formations and its effect on mechanical stratigraphy. Perras and Diederichs (2014) recorded that horizontal and vertical elastic characteristics may vary by 2-3 in the laminated shales, as either orientation or layering of preferred minerals occurs on scale smaller or smaller than log resolution. This anisotropy influences the accuracy of the results of the calculated properties and the correlation between these calculated properties and their connection to the in-situ mechanical behavior when hydraulic fracturing occurs.

**Clustering Algorithm Limitations:** Critical assessment of clustering algorithm assumptions behind the common use of mechanical facies classification algorithms has been published research. Jain (2010) observed that K-means cluster is based on the assumption of spherical clusters that are applicable with equal size that are not likely (not generally) to be the case when dealing in geological data where facies ranges tend to be gradational and cluster structure can be long, likely due to compositional gradients.

**Data Quality and Uncertainty Propagation:** The published literature points out that the quality of input log data is essential to the quality of mechanical facies classification, but log data quality problems are prevalent in working datasets. The researchers have recorded typical difficulties such as log calibration mistakes, depth integration into the results of various

logging runs, environmental impact witnessed on sonic measurements, and borehole conditions which influence density measurements (Vernik, 2016; Sondergeld *et al.*, 2010).

**Validation and Reproducibility Challenges:** One of the areas that were found to be very problematic in the published literature is that the measurement of mechanical facies classification in comparison with independent data is a critical issue. Mechanical facies are functional units in contrast to traditional lithofacies, which could be directly compared with descriptions of core, and these might lack visual analogs. The published studies have applied different validation techniques such as comparison with microseismic records (Zhao *et al.*, 2015), production correlations (Fjær *et al.*, 2008), and laboratory mechanical tests (Al-Ajmi and Zimmerman, 2006), yet the literature does not have standardized practice protocols.

**Future Directions and Research Needs** The literature review shows that there are a number of avenues of future research in mechanical stratigraphy and Frac-Driven Facies classification. Multi-scale associates multi-scale associates multi-scale combining multi-scale associates multi-scale associates of mechanical information with nanoindentation to core-scale to log scales through the generation of solid upscaling associations. Logging-while-drilling data has been suggested to perform real-time mechanical zonation but needs further progress in order to be put into practical use. Machine learning methods that use physics-based constraints on neural networks, such as rock physics, can provide possibilities of making more accurate predictions that make geological sense.

### Conclusion

This overall survey confirms that mechanical behavior is not an engineering parameter only, but a basic axis of subsurface heterogeneity that should be taken into consideration in the characterization of a reservoir in order to develop the subsurface optimally. Through the synthesis of published literature on cluster analysis of log-derived mechanical properties, we are able to show that Frac-Driven Facies can refine the traditional lithofacies interpretation in manners that have a direct effect on the reservoir behavior and engineering safety. The proposed dual-facies paradigm, based on the integration of depositional and mechanical stratigraphy, provides a more detailed and functional view of the subsurface, as indicated by several papers in unconventional and carbonate oil reservoirs

whereby diagenesis and fracturing overshadow the fluid circulation and rock behaviour.

The results in the published literature are consistently showing that production increases are 15-25% improvement in well completion through mechanical zonation guidance as compared to the well completion that previously was not considered. Although researchers find these elements problematic with regard to their methodology, such as the data requirements, uncertainty propagation, and difficulties in validation, there is substantial published evidence that gains affirmation to the value of usability of mechanical stratigraphy in building reservoirs. With the aim of the world achieving greater efficiency in energy consumption (UN SDG 7), climate action (UN SDG 13) and the accurate prediction of mechanical response is all the more important in hydrocarbon production as well as in geological carbon storage.

### References

- Aadnoy, B. S., and Looyeh, R. (2011). Petroleum rock mechanics: Drilling operations and well design. Gulf Professional Publishing.
- Al-Ajmi, A. M., and Zimmerman, R. W. (2006). Stability analysis of vertical boreholes using the Mogi–Coulomb failure criterion. *International Journal of Rock Mechanics and Mining Sciences*, 43(8), 1200–1211.
- Bachu, S. (2015). Review of CO<sub>2</sub> storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, 40, 188–202.
- Bhattacharya, J. P. (2006). Deltas. In Posamentier, H. W., and Walker, R. G. (Eds.), *Facies models revisited* (SEPM Special Publication 84, pp. 237–292). SEPM Society for Sedimentary Geology.
- Chopra, S., and Marfurt, K. J. (2007). Seismic attributes for prospect identification and reservoir characterization. Society of Exploration Geophysicists.  
<https://doi.org/10.1190/1.9781560801900>
- DUG. (2026). Explorationist. <https://dug.com/dug-insight/modules/explorationist/>
- EPCM Holdings. (2026). Hydraulic fracturing overview. <https://epcmholdings.com/hydraulic-fracturing-overview/>

Fjær, E., Holt, R. M., Horsrud, P., Raaen, A. M., and Risnes, R. (2008). *Petroleum related rock mechanics* (2nd ed.). Elsevier.

Gale, J. F. W., Reed, R. M., and Holder, J. (2007). Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments. *AAPG Bulletin*, 91(4), 603–622.

Gunter, G. W., Finneran, J. M., Hartmann, D. J., and Miller, J. D. (1997). Early determination of reservoir flow units using an integrated petrophysical method. *SPE Annual Technical Conference and Exhibition*. SPE 38679.

Guo, T., Zhang, S., Zou, Y., and Xiao, B. (2015). Numerical simulation of hydraulic fracture propagation in shale gas reservoir. *Journal of Natural Gas Science and Engineering*, 26, 847–856. <https://doi.org/10.1016/j.jngse.2015.07.024>

IPCC. (2005). *IPCC special report on carbon dioxide capture and storage*. In Metz, B., Davidson, O., de Coninck, H. C., Loos, M., and Meyer, L. (Eds.). Cambridge University Press.

Jain, A. K. (2010). Data clustering: 50 years beyond K-means. *Pattern Recognition Letters*, 31(8), 651–666. <https://doi.org/10.1016/j.patrec.2009.09.011>

Lateral Completions. (n.d.). *Hydraulic fracturing with dissolvable fracture plugs*. <https://lateralcompletions.com/hydraulic-fracturing/>

Laubach, S. E., Olson, J. E., and Gross, M. R. (2009). Mechanical and fracture stratigraphy. *AAPG Bulletin*, 93(11), 1413–1426. <https://doi.org/10.1306/07270909094>

Lu, J., Wilkinson, M., Haszeldine, R. S., and Fallick, A. E. (2009). Long-term performance of a mudrock seal in natural CO<sub>2</sub> storage. *Geology*, 37(1), 35–38.

Luck, R. (2014). Eagle Ford 'long outcrop' west of Del Rio TX [Photograph]. Flickr. <https://www.flickr.com/photos/royluck/15543245726>

Nelson, R. A. (2001). *Geologic analysis of naturally fractured reservoirs* (2nd ed.). Gulf Professional Publishing.

Passey, Q. R., Bohacs, K. M., Esch, W. L., Klimentidis, R., and Sinha, S. (2010). From oil-prone source rock to gas-producing shale reservoir —

geologic and petrophysical characterization of unconventional shale-gas reservoirs. *SPE International Oil and Gas Conference and Exhibition*, Beijing, China. SPE 131350.

Perras, M. A., and Diederichs, M. S. (2014). A review of the tensile strength of rock: Concepts and testing. *Geotechnical and Geological Engineering*, 32(2), 525–546.

Rickman, R., Mullen, M. J., Petre, J. E., Grieser, W. V., and 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.

Rider, M., and Kennedy, M. (2011). *The geological interpretation of well logs* (3rd ed.). Rider-French Consulting.

Schieber, J. (2011). Reverse engineering mother nature — shale sedimentology from an experimental perspective. *Sedimentary Geology*, 238(1–2), 1–22.

Shahnazi, A., Bahremandi, M., Ahmadi, A., Shahmoradi, M. H., Saemi, M., and Bagheri, A. M. (2024). Core sample selection based on MRGC method utilizing geomechanical units. *Carbonates and Evaporites*, 39(2), Article 57. <https://doi.org/10.1007/s13146-024-00968-z>

SLB. (2023, November 17). *Techlog wellbore stability*. <https://www.slb.com/products-and-services/delivering-digital-at-scale/software/techlog-wellbore-software/techlog/techlog-geomechanics/techlog-wellbore-stability>

Sondergeld, C. H., Newsham, K. E., Comisky, J. T., Rice, M. C., and Rai, C. S. (2010). Petrophysical considerations in evaluating and producing shale gas resources. *SPE Unconventional Gas Conference*. SPE 131768.

Su, X., Gong, L., Fu, X., Wang, Y., Gao, S., Wang, J., Qin, X., Luo, H., and Bao, T. (2023). Impact of mechanical stratigraphy on fracture growth and propagation. *Frontiers in Earth Science*, 11, Article 1253787. <https://doi.org/10.3389/feart.2023.1253787>

Suárez-Rivera, R., Deenadayalu, C., and Yang, Y.-K. (2009). Unlocking the unconventional oil and gas reservoirs: The effect of laminated heterogeneity in wellbore stability and completion of tight gas shale

reservoirs. Offshore Technology Conference. OTC 20159.

Tran, T. A., and Le, T. T. (2022). Unsupervised lithology clustering from well logs. Vietnam Journal of Earth Sciences, 44(3), 395–406.

Vernik, L. (2016). Seismic petrophysics in quantitative interpretation. Society of Exploration Geophysicists.

Vernik, L., and Nur, A. (1992). Ultrasonic velocity and anisotropy of hydrocarbon source rocks. Geophysics, 57(5), 727–735.

Walker, R. G., and Dalrymple, R. W. (Eds.). (2010). Facies models 4. Geological Association of Canada.

Wendt, W. A., Sakurai, S., and Nelson, P. H. (1986). Permeability prediction from well logs using multiple

regression. In Reservoir characterization (pp. 181–221). Academic Press.

Zakhour, N. (2015). 3D driven mineralogy and geomechanical property measurements from surface seismic data along horizontal wells monitored with microseismic: Application to the Wolfcamp Shale, Midland Basin, West Texas. SPE/SEG Unconventional Resources Technology Conference. URTeC: 2154178.

Zhao, T., Jayaram, V., Roy, A., and Marfurt, K. J. (2015). A comparison of classification techniques for seismic facies recognition. Interpretation, 3(4), SAE29–SAE58. <https://doi.org/10.1190/INT-2015-0044.1>

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