International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/

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Vol. 53 No. 2 November 2025, pp. 498-510

A Critical Review Of Geomechanical Controls On Basin Evolution And Fluid Migration: From Tectonic Stress To Seal Integrity

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Abstract: The integration of geomechanical principles into basin analysis has transitioned from a niche specialty to an indispensable component of modern subsurface evaluation. This shift is critical for reducing risk in conventional hydrocarbon exploration and production and is equally fundamental for emerging energy applications such as CO2 sequestration and geothermal energy. This review synthesizes the critical role of geomechanics in understanding the dynamic evolution of sedimentary basins and the complex, often transient, pathways of fluid migration. We focus on three key, interconnected areas: (1) the profound and often dominant influence of the tectonic stress field on the architecture of fluid migration pathways; (2) the dynamics of fault reactivation during basin development and its significant implications for fluid flow, seal breach, and hydrocarbon remigration; and (3) the impact of mechanical stratigraphy on the capacity and long-term integrity of seal rocks. By examining the intricate interplay between in-situ stress, rock mechanical properties, and pore fluid pressure, this article highlights the absolute necessity of a geomechanically-informed approach to accurately predict fluid distribution, assess trap and seal integrity, and optimize subsurface resource exploitation. We conclude by discussing the current challenges, particularly those related to model uncertainty and scale, and explore future directions where technological advancements, especially in coupled modeling and machine learning, are set to revolutionize integrated geomechanical-basin analysis.

Keywords: Geomechanics, Basin Analysis, Fluid Migration, Tectonic Stress, Fault Reactivation, Mechanical Stratigraphy, Seal Capacity, CO2 Storage, Geothermal Energy

Introduction

The Paradigm Shift: From Static to Dynamic Basin Models

The traditional approach to basin analysis, which solidified in the mid-20th century, has historically treated the subsurface as a largely static system. In this view, rock properties and geological geometries were assumed to remain relatively constant over geological time following their initial deposition and lithification. This perspective, while foundational for early exploration successes, is increasingly recognized as an oversimplification that fails to capture the dynamic nature of the Earth's crust. A significant paradigm shift, accelerating over the past three decades, is now well underway, driven by the fundamental recognition that sedimentary basins are

intensely dynamic systems. They evolve continuously in response to a complex interplay of tectonic forces, sediment loading, erosional unloading, and the pervasive influence of fluid flow.

This evolution in geological thinking is not accidental; it is underpinned by concurrent advancements in technology and computational power. The widespread adoption of high-resolution 3D and 4D seismic imaging has provided unprecedented views of subsurface architecture, revealing complex fault networks and fluid-flow indicators that defy static explanation (as illustrated by the foundational workflow in Figure 1). Simultaneously, the exponential growth in computing power has enabled the development of sophisticated 4D basin modeling, which explicitly considers the temporal evolution ("4D" being 3D space plus time) of the basin. More sophisticated models are able to depict interrelated processes such as tectonic deformation, erosion, compaction, and sedimentation with more precision. There are intricate connections between these processes. With this data, we can create a model that more accurately depicts the mechanical properties, pore pressure regime, and in-situ stress field of rocks throughout geological history (Bruch and Sassi, 2021).

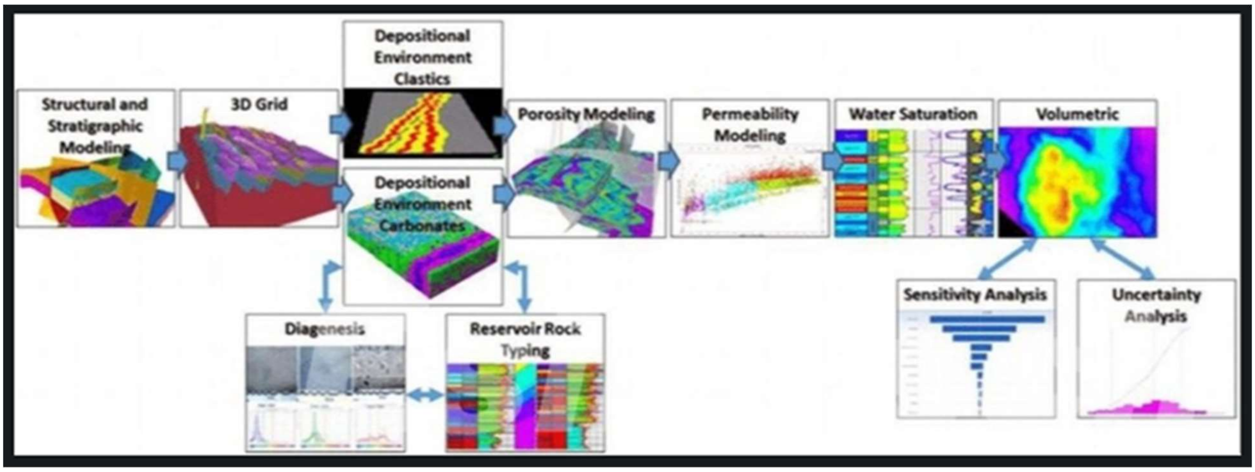

Figure 1: Example of a comprehensive geological modeling workflow.

The shift from static to dynamic models has significantly impacted the evaluation of subsurface resources and risk management, and this isn't limited to the academic realm. Fixing the two- or three-dimensional paths that fluids take, improving the accuracy of predicting when hydrocarbons will be produced, and thoroughly checking the long-term stability of geological traps are all possible. Because of the documentation of the basin's continuous development, all of these things are achievable. This is particularly important in complex geological settings, such as fold-and-thrust belts, salt-tectonic provinces, and inverted basins, where the stress field can vary significantly in both space and time, leading to highly complex histories of fluid flow, entrapment, leakage, and re-accumulation.

The Importance of Geomechanics in Subsurface Resource Evaluation

The principles of geomechanics—the study of how rocks and rock masses respond to forces—are fundamental to the successful exploration, development, and management of a wide range of subsurface resources.

- **Hydrocarbon Exploration and Production:** In the context of hydrocarbon exploration, geomechanics plays a crucial role in assessing the integrity of seals, predicting the risk of fault reactivation, and understanding the distribution and connectivity of natural fracture networks. A comprehensive geomechanical analysis can help determine whether a fault is likely to act as a permanent conduit for fluid flow, a barrier, or a dynamic feature that alternates between the two. This is a critical factor in assessing the prospectivity of a trap. In production, geomechanics is essential for optimizing well placement, preventing wellbore instability, managing reservoir compaction, and mitigating the associated risk of surface subsidence.
- **Geothermal Energy:** Geothermal energy extraction relies on the ability to circulate fluids through hot, often low-permeability, crystalline or sedimentary rock formations. The practice is widespread in EGSs, or enhanced geothermal systems. In order to increase the reservoir's permeability, hydraulic stimulation is used to access a fracture network within the reservoir. As a result, the social acceptability and financial feasibility of EGS projects are heavily reliant on

geomechanics' contributions to stimulation program development and improvement, critical risk assessment for induced seismicity, and fracture propagation forecasting (Paluszny & Zimmerman, 2025).

- **CO2 Storage:** Many believe that a crucial strategy to mitigate the impacts of climate change is the long-term storage of carbon dioxide (CO_2) in rocks. To be successful, a carbon dioxide storage project must be able to safely store massive quantities of carbon dioxide in a subterranean reservoir for thousands of years. Establishing the overall stability of the storage complex is the primary concern in geomechanics. This comprises the primary caprock as well as any fissures that may cause its collapse. To reduce the chances of induced seismicity, surface uplift, and carbon dioxide leakage, a comprehensive geomechanical study is required. Several significant geomechanical hazards associated with CO_2 storage were identified in a 2022 assessment of the topic. According to Song et al. (2023), risks that could arise include high pore pressure, failures of the caprock, reactivation of faults, and problems with the well's integrity.

Scope and Objectives of the Review

The purpose of this review article is to provide a comprehensive overview of the role geomechanics plays in studies that attempt to explain the formation and fluid flow through sedimentary basins. This review primarily aims to accomplish the following:

1. Consider the most fundamental geomechanical principles that govern sedimentary basins.
2. Finding out how the structure of the fluid migration pathways is affected by the strong tectonic stress field.
3. Elaboration on the process of fault reactivation and its impact on fluid flow as it occurs during basin development.
4. The effect of mechanical stratigraphy on the durability and functionality of seal rock is the focus of this investigation.
5. Recent developments, ongoing issues, and forthcoming trends in integrated geomechanical-basin analysis.

Following the steps outlined will ensure that this review serves as a valuable resource for those working in the fields of petroleum engineering, geology, and geophysics.

Methods

The literature review in the report is a summary of the most recent scientific research. The method involved looking through the main academic databases, which were Scopus, Web of Science, and GeoRef. Using these databases, the authors did a full search of all peer-reviewed publications. Geomechanics, basin analysis, fluid migration, tectonic stress, fault reactivation, seal integrity, mechanical stratigraphy, and coupled modeling were some of the keywords used in the search strategy. This list isn't all of them. The selection process was based on finished papers, review papers with the most citations, and new studies that showed new ways of doing things or using existing ones in new ways, especially when it comes to the energy transition. The literature search might have only looked at work from the last thirty years. This might have been done to keep track of how the modern idea of geomechanics and its models came to be. Despite this, it was also done to find specific groundbreaking research that had already been done. The points made and conclusions drawn in this paper come from putting together different pieces of relevant literature.

Fundamentals of Geomechanics in Sedimentary Basins

It is essential to have a solid grasp of geomechanics fundamentals in order to apply these concepts and incorporate them into basin analysis. Everything about in-situ stress, pore pressure, mechanical characteristics of rocks, and breaking was thoroughly covered in this section.

2.1 The In-Situ Stress Tensor (σv, σHmax, σhmin) and Stress Regimes

The crust is constantly experiencing stress regardless of whether engineering techniques such as drilling or injection are employed. This stress, known as the in-situ stress field, indicates the typical stress level in the Earth's crust. It is a three-dimensional stress state best described by the in-situ stress tensor. For most practical purposes, this tensor can be simplified to its three mutually perpendicular principal stresses: the vertical stress (σv) and the maximum ($\sigma Hmax$) and minimum ($\sigma hmin$) horizontal stresses.

International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
Vol. 53 No. 2 November 2025, pp. 498-510

The relative magnitudes of these three principal stresses define the stress regime, which, according to Anderson's theory of faulting, dictates the type of faulting that can occur:

- **Normal Faulting Regime (σv > σHmax > σhmin):** Occurs in areas of tectonic extension, such as continental rifts or at divergent plate boundaries. The vertical stress is the maximum principal stress, leading to the formation of normal faults.

- **Strike-Slip Faulting Regime (σHmax > σv > σhmin):** Characteristic of transform plate boundaries or areas with significant lateral shear. The vertical stress is the intermediate principal stress.
- **Reverse Faulting Regime (σHmax > σhmin > σv):** Found in compressional tectonic settings, like subduction zones or continental collision zones. The maximum horizontal stress is the dominant principal stress, causing the formation of reverse and thrust faults (Figure 2).

The stress regime profoundly influences the orientation and style of faulting and fracturing, thereby controlling the architecture of fluid migration pathways. The determination of these stresses in practice relies on a variety of data sources, including leak-off tests and minifrac tests in wells (to constrain σhmin), analysis of borehole breakouts and drilling-induced fractures (to determine the orientation of σHmax), and density log integration (to calculate σv).

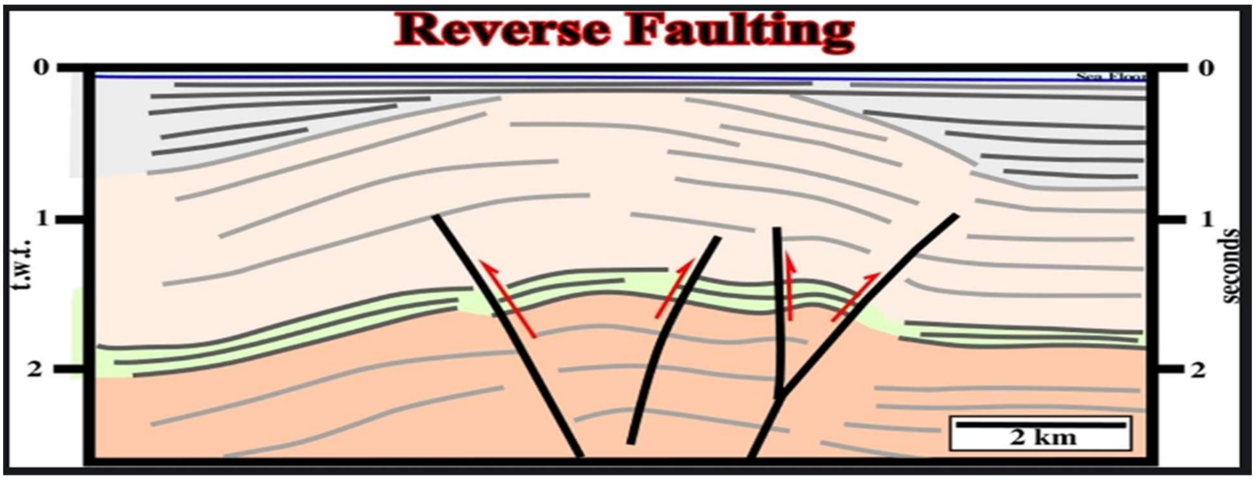

Figure 2: A diagram illustrating reverse faulting, a common feature in compressional tectonic regimes that shapes basin geometry.

Pore Pressure: Origin, Prediction, and Role in Effective Stress

Pore pressure is the pressure of the fluids (e.g., water, oil, gas) within the interconnected pore spaces of a rock. It is a critical parameter in geomechanics because it counteracts the total stress applied to the rock, thereby reducing the effective stress acting on the rock's solid skeleton. This, in turn, profoundly affects the strength and deformability of the rock.

The concept of effective stress (σ') was defined by Terzaghi and is expressed as:

$\sigma' = \sigma - \alpha P$
where:

- σ' is the effective stress
- σ is the total stress
- α is Biot's poroelastic constant (typically close to 1 for most geological applications)

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Vol. 53 No. 2 November 2025, pp. 498-510

- P is the pore pressure

Pore pressure can be generated by a variety of mechanisms, including compaction disequilibrium (where fluids cannot escape as fast as sediments are loaded), hydrocarbon generation, clay diagenesis, and fluid expansion due to heating. Accurate prediction of pore pressure is a critical aspect of geomechanical analysis, as it is essential for assessing the risk of wellbore instability, fault reactivation, and seal failure.

Rock Mechanical Properties: Elasticity, Strength, and Ductility

The mechanical properties of rocks describe how they respond to applied stresses. The key properties relevant to geomechanics are:

- **Elasticity:** The ability of a material to deform elastically under a load and return to its original shape when the load is removed. This is described by elastic moduli such as Young's modulus (a measure of stiffness) and Poisson's ratio (a measure of transverse strain).
- **Strength:** The ability of a rock to resist failure under an applied load, typically described by its unconfined compressive strength (UCS) and its tensile strength.
- **Ductility:** The ability of a material to deform plastically (permanently) without fracturing. Ductility is influenced by temperature, confining pressure, and strain rate. Ductile rocks, like salt, can flow over geological time, whereas brittle rocks, like many sandstones, will fracture.

Failure Mechanics: Mohr-Coulomb and Griffith Failure Criteria

Rock failure occurs when the applied stress exceeds its strength. Two of the most commonly used criteria to predict this are:

- **Mohr-Coulomb Failure Criterion:** An empirical criterion assuming that failure occurs when the shear stress (τ) on a plane reaches a critical value dependent on the normal stress (σn) on that plane. The criterion is expressed as:

$\tau = c + \mu\sigma n$
where c is cohesion and μ is the coefficient of internal friction. This criterion is exceptionally useful for predicting shear failure along faults.

- **Griffith Failure Criterion:** A theoretical criterion based on the assumption that failure initiates at the tip of a pre-existing crack or flaw when the stress concentration exceeds a critical value. It is particularly effective for predicting the tensile failure of brittle rocks.

Key Focus Area 1: Tectonic Stress Influence on Migration Pathways

The tectonic stress field is a fundamental control on the architecture of fluid migration pathways. The magnitude and orientation of the in-situ stresses, in conjunction with the pre-existing rock fabric, determine the permeability of fractures and faults, and thus the direction and rate of fluid flow. As conceptually shown in Figure 3, geological structures created and modified by stress regimes act as primary conduits for fluid movement, leading to features like pockmarks from seepage or mounds from pressure build-up.

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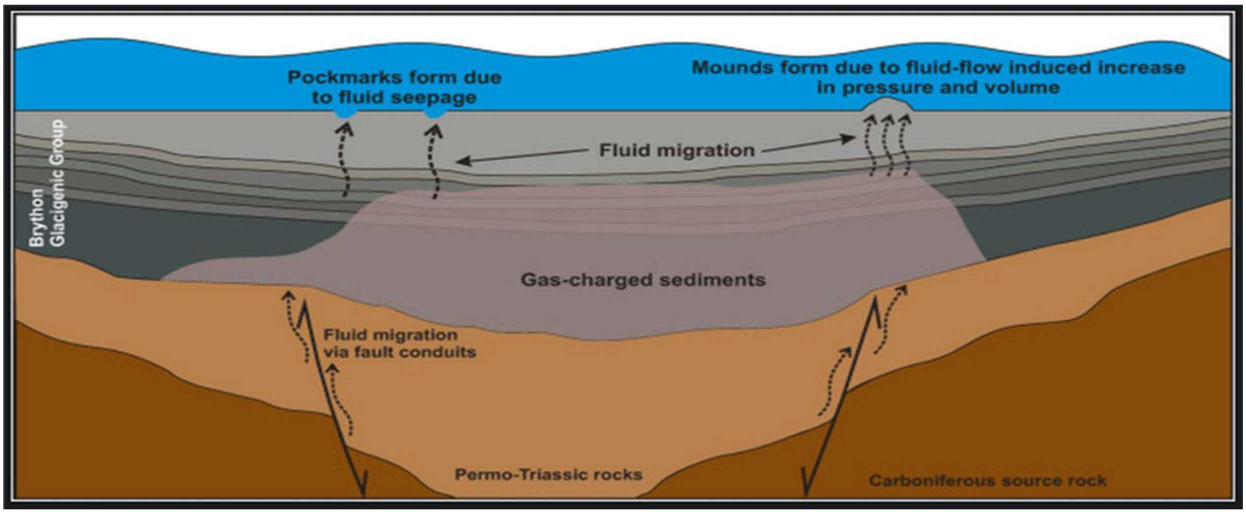

Figure 3: Conceptual diagram showing fluid migration pathways influenced by geological structures and stress regimes.

The structural evolution of a basin under a given tectonic regime dictates the large-scale framework for these pathways. For example, in strike-slip settings, a sequence of structures develops with increasing displacement, evolving from early "en-echelon" folds and faults to fully developed wrench-faulted zones that can uplift and erode previous structures (Figure 4). Understanding this tectonic evolution is key to mapping the history of fluid migration.

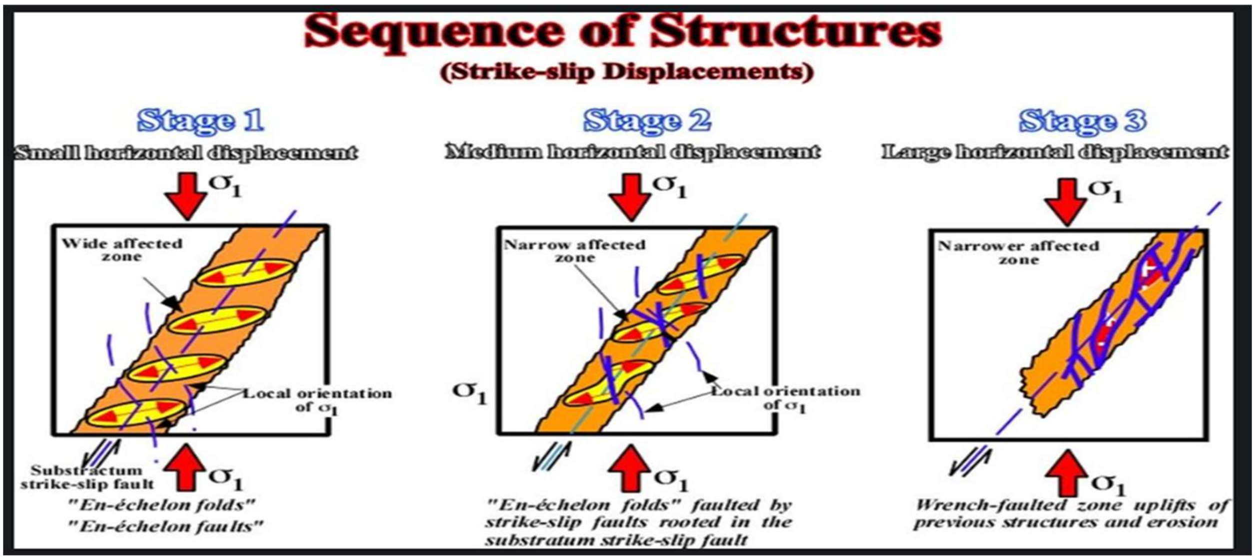

Figure 4: Illustration of sequence structures within a strike-slip system, demonstrating the impact of progressive tectonic processes on sedimentary layers and the creation of complex fault networks.

Stress-Induced Anisotropy and its Effect on Fluid Flow

In many sedimentary basins, the in-situ stress field is anisotropic ($\sigma Hmax \neq \sigma hmin$). This stress anisotropy leads to a preferred orientation of open, conductive fractures, resulting in directional permeability. Generally, fractures oriented parallel to the maximum horizontal stress ($\sigma Hmax$) will be more likely to be open and act as conduits for flow, while fractures oriented perpendicular to $\sigma Hmax$ will be more likely to be closed. This directional behavior is a direct consequence of the anisotropic nature of rock strength, where the resistance to shear failure is highly dependent on the orientation of pre-existing weaknesses relative to the applied stress field (Figure 5).

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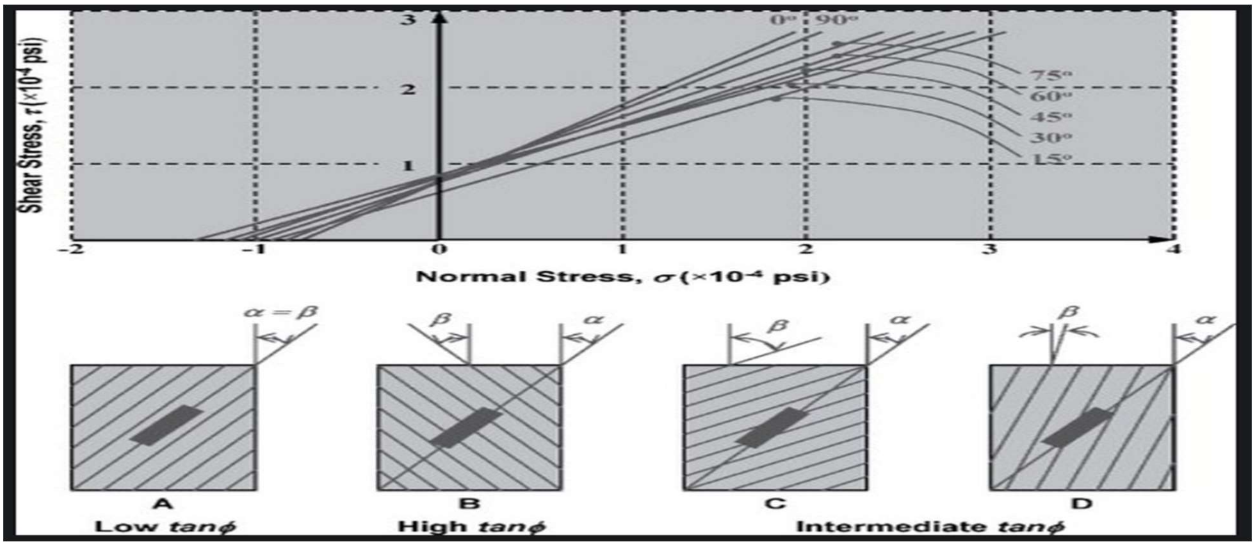

Figure 5: Anisotropic rock behavior illustrated by a Mohr diagram showing failure envelopes dependent on the angle of weakness planes relative to principal stress. The diagrams below show how fracture orientation (β) relative to the maximum principal stress (α) influences stability.

This stress-induced anisotropy has a profound effect on fluid flow, leading to the development of preferential migration pathways. In a strike-slip stress regime, for example, fractures oriented parallel to σHmax will be the most conductive, channeling fluid flow in that direction. This can result in permeability anisotropy that can exceed a 10:1 or even 100:1 ratio in the preferred flow direction compared to the perpendicular direction, a phenomenon well-documented in many fractured reservoirs (Sayers, 1990).

The Concept of Critically Stressed Fractures

A critically stressed fracture is a pre-existing fracture oriented optimally for shear failure under the current stress field. These fractures are thought to be highly conductive because the shear stress acting on them is sufficient to keep them open, even against a high normal stress. The tendency of a fracture to slip is often quantified by the slip tendency (the ratio of shear stress to normal stress). Mapping the orientation of critically stressed fractures allows for the prediction of fluid flow direction and the identification of potential migration pathways.

Paleo-stress and its Role in the Development of Ancient Migration Networks

The fluid migration pathways active today are often legacies of geological processes that occurred millions of years ago. The paleo-stress field—the stress field that existed in the past—played a critical role in developing these ancient networks. Reconstructing the paleo-stress field provides invaluable insights into the evolution of fluid migration pathways and the factors that controlled hydrocarbon accumulation. However, this reconstruction is challenging, as it relies on interpreting geological indicators like fault-slip data, slickensides, and fracture patterns, which may represent the superposition of multiple tectonic events over geological time (Heeremans, Larsen, & Stel, 1996).

Key Focus Area 2: Fault Reactivation During Basin Development

Faults are ubiquitous structures in sedimentary basins. Their behavior as either conduits or barriers to fluid flow is a critical factor in the development of a successful petroleum system. The reactivation of pre-existing faults in response to changes in the stress field or fluid pressure can have a profound impact on the integrity of traps and the migration of hydrocarbons.

Principles of Fault Stability and Reactivation

A fault's stability is governed by the balance between the shear stress promoting slip and the frictional resistance opposing it. Reactivation occurs when the shear stress exceeds this resistance. The key controlling factors are:

- The orientation of the fault with respect to the in-situ stress field.
- The magnitude of the shear and normal stresses on the fault plane.
- The frictional properties of the fault.
- The pore pressure within the fault zone, which reduces the effective normal stress and thus the frictional resistance (Climate Sustainability Directory, 2024).

Complex fault networks, as seen in map view (Figure 6) and in outcrop (Figure 7), provide the structural template upon which these reactivation processes act, creating a dynamic plumbing system within the basin.

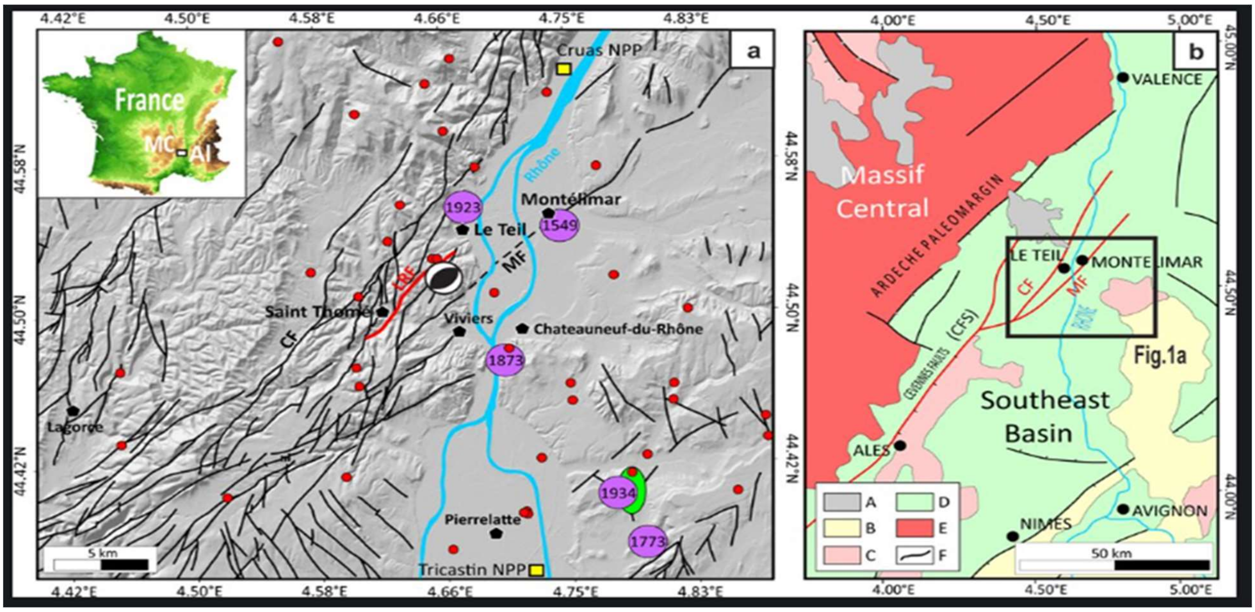

Figure 6: Visual representation of a complex fault network and displacement in the Southeast Basin, France. Such maps are crucial for assessing the potential for fault reactivation.

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Vol. 53 No. 2 November 2025, pp. 498-510

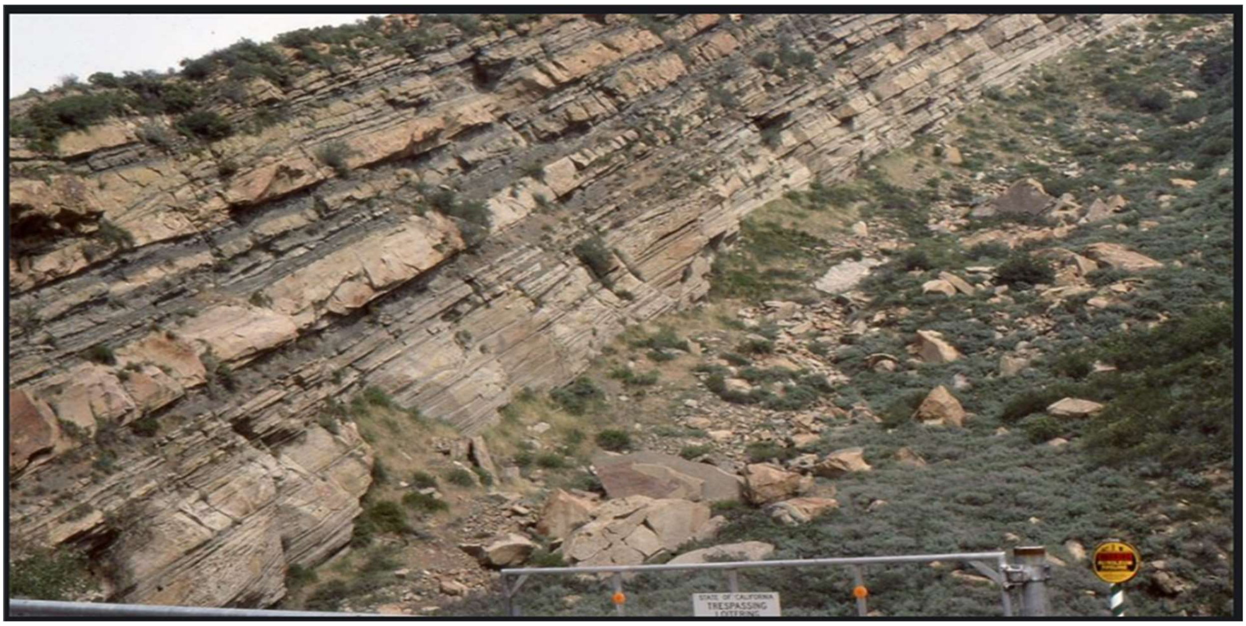

Figure 7: An outcrop example of layered and deformed geological features indicative of a strike-slip basin, providing a field-scale view of the structures susceptible to reactivation.

The Impact of Fault Reactivation on Petroleum Systems

- **Breaching of Seals and Remigration of Hydrocarbons:** Perhaps the most significant impact of fault reactivation is the breaching of seals. A reactivated fault can create a pathway for hydrocarbons to escape an existing trap, leading to their remigration to a shallower depth or to the surface. This process is a primary cause of failed traps and has been documented globally. For example, in the Halten Terrace area of offshore Norway, the reactivation of faults during the Cenozoic has been directly linked to the remigration of hydrocarbons from older Jurassic traps into younger, shallower traps. A 2002 study in the northern North Sea also found a strong correlation between the leakage potential of reservoir-bounding faults and the observed hydrocarbon column heights (Wiprut & Zoback, 2002).
- **Creation of Transient, High-Permeability Pathways:** Fault slip can create a temporary zone of fractured rock around the fault plane, which can be highly permeable. This transient pathway can be crucial for hydrocarbon migration, especially in otherwise low-permeability rocks.

Key Focus Area 3: Mechanical Stratigraphy and its Impact on Seal Capacity

Mechanical stratigraphy recognizes that the mechanical properties of rocks vary significantly with lithology, and this heterogeneity profoundly impacts deformation and failure. In the context of seal capacity, mechanical stratigraphy is a critical control on the integrity of top seals.

The Concept of Mechanical Stratigraphy: Lithology is not Destiny

Traditional stratigraphy focuses on correlating rock units based on their lithological and paleontological characteristics. Mechanical stratigraphy, however, subdivides the stratigraphic column into units based on their mechanical behavior (e.g., stiff, soft, brittle, ductile), as

illustrated by the distinct layers in Figure 8. This is crucial because rocks with different mechanical properties will respond differently to the same stress field.

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https://ijpsat.org/
Vol. 53 No. 2 November 2025, pp. 498-510

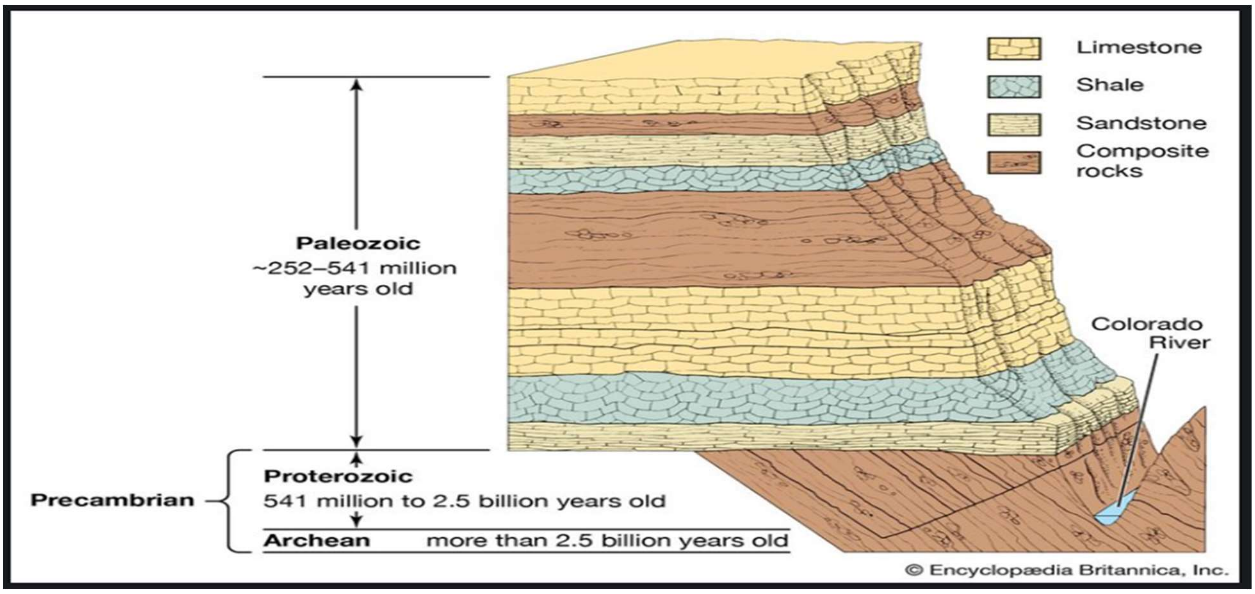

Figure 8: An illustration of distinct rock layers (mechanical stratigraphy), showing how a geological column is composed of units with varying mechanical properties (e.g., stiff limestones, brittle sandstones, and ductile shales).

The Role of Mechanical Interfaces in Focusing Stress and Strain

Mechanical interfaces, the boundaries between rock units with different mechanical properties, are critical zones for focusing stress and strain. When a layered sequence is subjected to stress, strain will concentrate at these interfaces—for example, at the boundary between a stiff, brittle sandstone and a soft, ductile shale. This can lead to the development of fractures and faults at these interfaces, which can in turn create potent pathways for fluid flow, potentially compromising an otherwise effective seal.

Contrasting Mechanical Behavior of Different Lithologies

A rock's first-order mechanical behavior dictates its quality, regardless of whether it is a reservoir or a seal. Table 1, which is available here, provides a synopsis of the most significant lithologies.

Table 1: *Mechanical Behavior of Common Seal and Reservoir Lithologies*

Lithology	Typical Mechanical Behavior	Seal Quality
Salt	Highly Ductile	Excellent
Shale	Ductile to Brittle	Good to Poor
Sandstone	Brittle	Poor
Carbonates	Highly Variable	Variable

Geomechanical Controls on Seal Capacity

In order to trap hydrocarbons, the geomechanics of a seal are controlled by a number of interrelated factors:

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https://ijpsat.org/
Vol. 53 No. 2 November 2025, pp. 498-510

- **Ductility vs. Brittleness:** A ductile material, such as salt, is ideal for a seal because it can undergo a transformation under stress without easily breaking. A brittle seal, however, is more likely to fracture, creating leakage pathways.
- **Minimum Horizontal Stress (σhmin) as a Limit on Seal Capacity:** This is often considered the ultimate limit on seal capacity. If the fluid pressure in a reservoir exceeds the σhmin in the overlying seal, it will induce hydraulic fractures, causing the seal to fail.

Integrated Geomechanical-Flow Modeling

The complex, two-way interplay between fluid flow and geomechanics necessitates the use of coupled models that can simulate the dynamic evolution of fluid migration systems.

The Need for Coupled Models: Poroelasticity and Beyond

Traditional basin models often treat fluid flow and geomechanics as separate processes. However, in reality, they are intimately linked through poroelasticity: changes in fluid pressure cause the rock matrix to deform, which in turn alters permeability and affects fluid flow. This requires an iterative coupling scheme where information is constantly exchanged between fluid flow and geomechanical simulators to achieve a converged solution (Figure 9). A 2021 study highlighted that classical simulators based on simple vertical compaction are only suitable for basins not subjected to significant tectonic deformation, underscoring the need for fully coupled models in most real-world settings (Brüch et al., 2021).

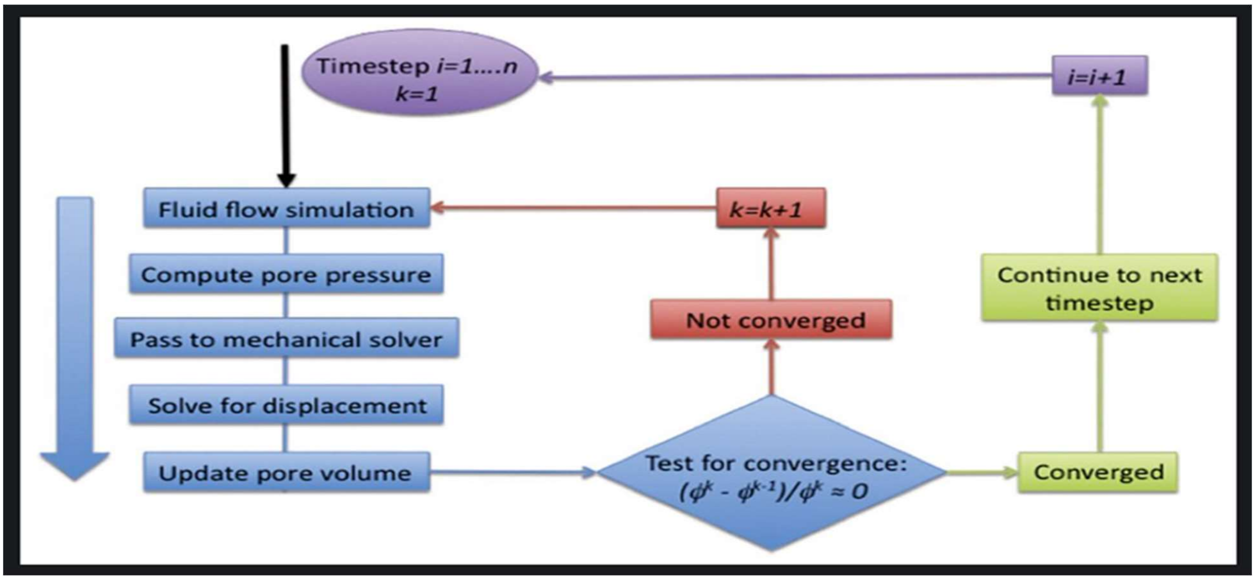

Figure 9: A flowchart illustrating an iterative coupling scheme, emphasizing the exchange of information between fluid flow and geomechanical simulators to solve for pressure, stress, and deformation.

Beyond poroelasticity, other important couplings must be considered in many applications:

- **Thermo-mechanical coupling:** In geothermal systems or deep reservoirs, temperature changes can cause thermal expansion or contraction of both the rock matrix and pore fluids. This induces thermal stresses that can alter the in-situ stress field, potentially leading to rock failure or fracture propagation, which is a critical consideration in designing and managing geothermal reservoirs.
- **Chemo-mechanical coupling:** The mechanical properties of rocks can be altered through chemical reactions with fluids, which can have practical applications such as diagenesis and carbon dioxide storage. For instance, when carbon dioxide and brine are thoroughly mixed, the rock becomes porous and easily broken down, allowing carbonate cements to dissolve.

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Vol. 53 No. 2 November 2025, pp. 498-510

But mineral precipitation can do the opposite, making the rock both stronger and less porous. For reliable long-term predictions of a carbon storage site's stability, it is essential to model these effects.

Discussion: Challenges and Future Directions

Uncertainty and Scale in Geomechanical Modeling

The input parameters, including the paleo-stress field's precise conditions and the rock properties outside the well control area, are fraught with uncertainty. Because of this, geomechanical modeling is currently encountering a significant new challenge. Second, and most importantly, we must address the matter of scale. Geomechanics encompasses a wide range of topics, from localized rock fissures to fault systems that impact entire basins. The best way to use multiscale modeling approaches to establish connections between these scales is an open question at the moment.

The Role of Machine Learning and Artificial Intelligence

A paradigm shift is on the horizon for geomechanics as a result of developments in artificial intelligence (AI) and Machine learning (ML). This technology is capable of the following:

- **Automate model building:** Seismic data can be automatically interpreted by machine learning algorithms by first being transformed into rock models. This feature is currently available.
- **Improve model accuracy:** When it comes to solving the equations that control coupled geomechanical processes, advanced algorithms like physics-informed neural networks (PINNs) really shine. When compared to more conventional numerical algorithms, these make workflow management much easier and faster. Generational adversarial networks (GANs) can precisely identify geologic fracture networks with minimal training data.
- **Quantify and manage uncertainty:** Uncertainty can be measured and its causes identified with the help of machine learning, which facilitates the execution of numerous model scenarios. The rapid development of artificial intelligence (AI) and data-driven methods

  is causing the field to move swiftly and devise new solutions to the challenging problems that arise, according to a recent study.

Application to the Energy Transition

The energy transition is making an incorrect use of geomechanics standards:

- **Geothermal Energy:** Borehole stability checks, hydraulic fracturing program planning, and induced seismicity risk management are all areas where geomechanical analysis is put to use, according to Paluszny and Zimmerman (2025).
- **Carbon Sequestration:** You can determine the stability of the storage site, the likelihood of CO2 leakage, and the likelihood of earthquakes caused by the site using geomechanics (Paluszny and Zimmerman, 2025).

An ever-growing role for geomechanics is anticipated as the global community strives for a low-carbon energy paradigm and cultivates a heightened sense of environmental consciousness.

Conclusions

The significance of geomechanics in comprehending the formation of sedimentary basins and the complicated movement of fluids is summed up in this review. The subsequent findings were of paramount importance:

- An essential and valuable process can be accomplished by utilizing geomechanical principles in basin analysis to transform static models into dynamic ones.
- One of the most crucial factors influencing the movement of fluids is the strength of the in-situ stress field. Faults and fractures become permeable in part because of this stress field.

- Seals can be broken and massive quantities of hydrocarbons can be redeposited in the event of a petroleum system disruption. This is the situation because mistakes can happen unintentionally.
- Assuming the existence of mechanical stratigraphy is the most critical step in comprehending the geomechanical characteristics of sediment layers and the operation of well seals.
- To represent the dynamic nature of fluid migration systems, coupled geomechanical-flow models are required. These models must account for poro-, thermo-, and chemocoupled phenomena.
- Geothermal power and carbon capture are two examples of energy transition technology. In order for these technologies to function properly, geomechanics—a significant and practical science—is required.

Geomechanics is no longer seen as a niche field because it has been integrated into basin analysis. It is now an important part of modern assessments of subsurface conditions. It is important to fully understand these principles in order to lower the risks of hydrocarbon exploration and speed up the development of new energy technologies. Geomechanics helps predict where hydrocarbon deposits will be located, lowers the number of well failures, finds the best places for wells and fractures to grow, lowers the risk of induced seismicity, and makes CO2 storage sites safer. As our knowledge grows, we will be better able to do numerical calculations, and geomechanics and related methods will play a bigger part in reducing risk below the ground.

References

[1]. Brüch, A., Colombo, D., Frey, J., Berthelon, J., Cacas-Stentz, M. C., Cornu, T., & Gout, C. (2021). Coupling 3D geomechanics to classical sedimentary basin modeling: From gravitational compaction to tectonics. Geomechanics for Energy and the Environment, 28, 100259. https://doi.org/10.1016/j.gete.2021.100259

[2]. Paluszny, A., & Zimmerman, R. W. (2025). The role of subsurface geomechanics in the green energy transition. *Royal Society Open Science, 12*(5), 241516. https://doi.org/10.1098/rsos.241516

[3]. Heeremans, M., Larsen, B. T., & Stel, H. (1996). Paleostress reconstruction from kinematic indicators in the Oslo Graben, southern Norway: New constraints on the mode of rifting. Tectonophysics, 266(1–4), 55–79. https://doi.org/10.1016/S0040-1951(96)00183-7

[4]. Sayers, C. M. (1990). Stress-induced fluid flow anisotropy in fractured rock. *Transport in Porous Media, 5*(3), 287-297. https://doi.org/10.1007/BF00140017

[5]. Song, Y., Jun, S., Na, Y., Kim, K., Jang, Y., & Wang, J. (2023). Geomechanical challenges during geological CO_2 storage: A review. Chemical Engineering Journal, 456, 140968. https://doi.org/10.1016/j.cej.2022.140968

[6]. Climate Sustainability Directory. (2024). Fault reactivation. https://climate.sustainability-directory.com/term/fault-reactivation/

[7]. Wiprut, D., & Zoback, M. D. (2002). Fault reactivation, leakage potential, and hydrocarbon column heights in the northern North Sea. In A. G. Koestler & R. Hunsdale (Eds.), Norwegian Petroleum Society Special Publications (Vol. 11, pp. 203–219). Elsevier. https://doi.org/10.1016/S0928-8937(02)80016-9