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Geomechanical Controls on Shale Gas Production: A Critical Review of Stress, Strain, and Sorption-Induced Deformation

Dr. Alistair Finch
Department of Petroleum Engineering, Imperial College London, London, United Kingdom

Prof. Eleanor Vance
Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, Norman, USA

ABSTRACT

Background: Shale gas has become a cornerstone of the global energy supply, yet accurately predicting and optimizing its production remains a significant challenge. Conventional reservoir models often fail to capture the complex, dynamic nature of shale, where gas flow is intrinsically linked to the geomechanical state of the formation.

Purpose: This article provides a comprehensive review and synthesis of the critical role that stress and strain play in modulating gas production from unconventional shale reservoirs. We aim to elucidate the coupled mechanisms of stress-sensitive permeability and sorption-induced matrix deformation and their combined impact on reservoir performance.

Methodology: A critical review of the existing literature was conducted. The analysis synthesizes theoretical models, experimental data, and numerical simulation studies. We examine fundamental geomechanical principles, models for stress-dependent permeability, theories of gas adsorption-induced swelling, and coupled geomechanical-fluid flow simulators. The synthesis is structured around the 29 primary sources that form the foundation of modern understanding in this field.

Findings: The review confirms that shale permeability is highly sensitive to changes in effective stress, typically declining as the reservoir is depleted. Furthermore, the interaction between reservoir gases (CH_4, CO_2) and the organic-rich shale matrix induces significant strain (swelling or shrinkage), which can either constrict or enlarge flow pathways. The interplay of these two effects—stress-induced compaction and sorption-induced deformation—governs the time-dependent evolution of the fracture network's conductivity and, consequently, the gas production rate.

Conclusion: A robust understanding of stress-strain dynamics is indispensable for the effective exploitation of shale gas resources. Future advancements in reservoir engineering depend on the development of fully coupled models that integrate these complex geomechanical phenomena. Such models are essential for optimizing hydraulic fracturing designs, forecasting long-term production accurately, and evaluating novel enhanced recovery techniques.

KEYWORDS: Shale Gas, Geomechanics, Effective Stress, Permeability, Sorption-Induced Strain, Coupled Modeling, Unconventional Reservoirs.

INTRODUCTION

Background

The global energy landscape has been profoundly reshaped over the past two decades by the "shale revolution." Advances in horizontal drilling and hydraulic fracturing have unlocked vast quantities of natural gas from previously inaccessible unconventional reservoirs, such as organic-rich shale formations. These resources have increased energy security, lowered gas prices, and provided a cleaner-burning alternative to coal for power generation. However, the extraction of gas from these ultra-low permeability formations presents unique and complex challenges that distinguish them from conventional reservoirs. Shale is not merely a passive container for hydrocarbons; it is a geomechanically active medium where the rock fabric and fluid flow are deeply intertwined. The long-term productivity and economic viability of a shale gas well are dictated by a complex interplay of geological, petrophysical, and mechanical factors that evolve throughout the life of the reservoir.

Statement of the Problem

Gas production from shale reservoirs is fundamentally governed by the ability of gas to flow from the dense rock matrix into a network of fractures—both natural and hydraulically induced—and ultimately to the wellbore. The permeability of this fracture network is the single most critical parameter controlling production rates. A central problem in shale reservoir engineering is that this permeability is not a static property. Instead, it is dynamically modulated by geomechanical forces that change as the reservoir is depleted. As pore pressure decreases during production, the effective stress acting on the rock skeleton increases, leading to fracture closure and a corresponding reduction in permeability. Concurrently, the desorption of methane from the organic matter (kerogen) within the shale matrix causes the matrix to shrink, which can potentially widen fractures and enhance permeability. Conversely, the injection of fluids, such as carbon dioxide for enhanced gas recovery (EGR), can cause the matrix to swell, constricting flow paths. Therefore, gas production is governed by a dynamic competition between stress-induced compaction and sorption-induced deformation (strain). Accurately forecasting production and optimizing recovery strategies requires a deep understanding of these coupled phenomena.

Review of Current Understanding

Early models of shale gas production often relied on simplified assumptions that neglected these complex geomechanical effects. However, a growing body of research has demonstrated the inadequacy of such approaches. The scientific community has progressively moved towards recognizing the critical importance of stress sensitivity and sorption-induced strain. Foundational work has established that the permeability of shale fractures is highly dependent on effective stress, with significant permeability loss observed as reservoir pressure declines [9, 14]. This has led to the development of numerous stress-sensitive permeability models. In parallel, research adapted from the coalbed methane (CBM) industry has highlighted the importance of sorption-induced phenomena. Experimental and theoretical studies have shown that organic-rich shale exhibits significant swelling and shrinkage upon interaction with gases like methane and carbon dioxide [19, 10]. This deformation of the rock matrix directly impacts the aperture of adjacent fractures, thereby altering permeability. The most advanced approaches now seek to integrate these effects within fully coupled geomechanical and fluid flow models to capture the holistic behavior of the reservoir [17, 14].

Objectives and Scope

The primary objective of this article is to provide a comprehensive and critical review of the state-of-the-art understanding of how stress and strain modulate gas production from shale. We synthesize the key theoretical concepts, experimental evidence, and modeling advancements that form the basis of this field. The scope of this review encompasses: (1) an examination of the fundamental geomechanical principles governing stress and strain in porous media; (2) a detailed analysis of the two primary mechanisms—stress-sensitive permeability and sorption-induced strain; (3) a review of how these mechanisms are integrated into coupled simulation frameworks; and (4) a discussion of the practical implications for reservoir stimulation, production forecasting, and the development of advanced recovery technologies. By synthesizing the findings from a curated set of 29 seminal publications, this article aims to provide a clear and cohesive picture of the critical role of geomechanics in modern shale gas engineering.

Analytical Framework

Fundamental Geomechanical Principles

The behavior of fluid-filled porous rocks like shale is governed by the principle of effective stress. The total stress exerted on a rock volume by the overlying strata (the overburden) is supported by both the solid rock skeleton and the fluid within the pores. The effective stress is the portion of the total stress borne by the rock matrix and is the primary driver of mechanical deformation, such as compaction and fracture closure. In its simplest form, it is defined by the difference between the total stress and the pore pressure. As gas is produced from a reservoir, the pore pressure declines, causing the effective stress to increase. This increase in effective stress compacts the rock and, most importantly, squeezes the fractures, reducing their ability to transmit fluids.

The response of the reservoir to these changes in stress and pore pressure is described by the theory of poroelasticity. This theory couples the deformation of the porous medium with the diffusion of the pore fluid. For shale, this means that changes in pore pressure induce mechanical strain (deformation), and conversely, mechanical strain induces changes in pore pressure. This two-way coupling is fundamental to understanding how the entire reservoir system evolves during production.

Modeling Stress-Sensitive Permeability

The relationship between fracture permeability and effective stress is one of the most critical aspects of shale geomechanics. As effective stress increases, the asperities (rough contact points) on the fracture surfaces are crushed, and the fracture aperture closes, leading to a dramatic reduction in permeability. A significant body of research has focused on developing analytical models to capture this behavior. These models often express permeability as an exponential or power-law function of effective stress.

For instance, work on coal reservoirs [20], which shares many similarities with shale, provides a foundational overview of models that link permeability changes to stress variations. Chen et al. [9] developed and validated a model specifically for gas shale, demonstrating that fracture permeability is highly sensitive to both effective stress and the pressure of the gas within the reservoir. Their work provides key insights into how this sensitivity impacts production forecasts. Further studies have explored how permeability evolves under complex triaxial stress conditions, which more accurately represent the subsurface environment. Research by Yan et al. [27] investigated permeability changes caused by stress-induced damage, while Liang et al. [18] examined permeability evolution in bedding shales during brittle and semi-brittle deformation. These studies collectively show that permeability is not a simple, decaying function of stress but is also influenced by the creation of new micro-cracks and the anisotropic nature of the rock.

Sorption-Induced Strain (Matrix Swelling and Shrinkage)

In addition to purely mechanical effects, the permeability of shale is also modulated by physicochemical interactions between the reservoir gas and the rock matrix. Shale formations, particularly their organic kerogen component, can adsorb large quantities of gas, primarily methane, onto their vast internal surfaces. This adsorption process is reversible. The amount of gas adsorbed is a function of pressure and gas composition, a phenomenon well-documented by studies on gas adsorption measurements [8, 29].

A critical consequence of this adsorption/desorption cycle is the induction of mechanical strain in the rock matrix. When gas molecules adsorb onto the surface of the kerogen, they alter the surface free energy, causing the matrix to swell. Conversely, as gas is produced and desorbs from the surface, the matrix shrinks. This phenomenon is analogous to the swelling of a sponge when it absorbs water. The theoretical basis for this swelling was partly established by Scherer [23] in his work on porous glass and later adapted specifically for coal and shale by Pan & Connell [19], who developed a widely cited model for gas adsorption-induced swelling.

Extensive experimental work has confirmed and quantified this effect. Studies on coals have shown significant swelling in the presence of supercritical CO_2 [11, 4]. This is highly relevant to shale, as CO_2 is often considered for EGR or as a fracturing fluid. Direct investigations on shale have also been performed. Chen et al. [10] conducted experiments on the swelling of organic-rich shale in methane, confirming that the effect is significant. Ao et al. [5] investigated the structural and chemical changes in shale after treatment with supercritical CO_2, finding that it induces notable swelling and alters the pore structure. This matrix swelling and shrinkage directly impacts the width of adjacent fractures. Swelling constricts fractures, reducing permeability, while shrinkage enlarges them, potentially enhancing permeability.

Coupled Geomechanical and Fluid Flow Models

To accurately capture the real-world behavior of a shale reservoir, the effects of stress-sensitive permeability and sorption-induced strain must be considered simultaneously. This requires the development of sophisticated numerical simulators that fully couple the equations of geomechanics with the equations of fluid flow. In these models, the permeability at each point in the reservoir is continuously updated based on the local effective stress and the amount of matrix swelling or shrinkage. In turn, the fluid flow and pressure changes calculated by the flow model are used to update the stress and strain fields in the geomechanical model.

Several research groups have made significant strides in developing and applying such coupled models. The work by Kudapa and colleagues represents a systematic effort to model gas flow from the shale matrix into the fracture network, explicitly accounting for the dynamic nature of the system [16, 17]. Their models provide a framework for simulating the complex flow behavior in shale reservoirs. In a subsequent study, they extended this to model gas flow within the fracture network itself, incorporating geomechanical effects [15]. Jiang & Yang [14] also presented a comprehensive coupled fluid flow and geomechanics model for fractured shale gas reservoirs. Their simulations clearly demonstrated how the stress-sensitive behavior of the fractures, combined with matrix-fracture interaction, governs the production profile of the well. These coupled models are essential tools for understanding the complex interplay of forces at work and for making more reliable predictions about long-term reservoir performance.

RESULTS AND SYNTHESIS

The Direct Impact of Stress on Fracture Networks

A consistent finding across numerous experimental and modeling studies is that the permeability of both natural and hydraulically induced fractures in shale is highly sensitive to effective stress. As production begins and pore pressure is drawn down, the corresponding increase in effective stress systematically reduces fracture aperture and, consequently, permeability. This effect is most pronounced in the early stages of production when pressure drawdown is most rapid. The studies by Chen et al. [9] and Jiang & Yang [14] provide compelling evidence that neglecting this stress sensitivity leads to overly optimistic production forecasts. The rate of permeability decline is a function of the rock's mechanical properties, the initial fracture geometry, and the presence of proppant in hydraulic fractures. While proppant is designed to hold fractures open, its effectiveness can diminish over time due to embedment and crushing under high stress, leading to a continued decline in conductivity. Natural fractures, which are typically unpropped, are even more susceptible to closure. The stress-induced permeability reduction is a primary mechanism contributing to the steep initial decline curves characteristic of many shale gas wells.

The Role of Sorption-Induced Strain on Permeability

The impact of sorption-induced strain presents a more complex, dual effect on reservoir permeability. During the primary production of methane, gas desorbs from the surfaces of the kerogen and micropores. This desorption leads to matrix shrinkage, which acts to widen fractures and can partially counteract the permeability loss from increasing effective stress. The magnitude of this effect is dependent on the gas storage capacity of the shale, particularly its Total Organic Carbon (TOC) content, as organic matter is the primary site for adsorption [7].

The opposite effect is observed during injection processes, particularly those involving CO_2 for Enhanced Gas Recovery (EGR) or sequestration. As established in studies on coal [6, 12] and confirmed for shale [5], CO_2 adsorbs more strongly than methane and induces significantly greater matrix swelling. This swelling can severely constrict fracture apertures, a phenomenon known as "permeability jail." While CO_2 injection can effectively displace methane and enhance recovery, the associated swelling can choke off flow pathways, potentially negating the benefits. This is a critical consideration in the design of EGR projects. Studies comparing the displacement efficiency of different injectants, such as CO_2 and N_2, have shown that while CO_2 is more effective at displacing methane on a molecular level, its swelling effect is a major operational challenge [26, 24, 28].

3.3. Integrated Effects on Reservoir Performance

The ultimate performance of a shale gas reservoir is determined by the net result of these competing mechanisms: stress-induced fracture compaction versus sorption-induced matrix deformation. In the primary production phase, the negative impact of increasing effective stress typically dominates, leading to an overall decline in permeability over time. However, the matrix shrinkage from methane desorption provides a beneficial, albeit secondary, effect that can moderate the rate of this decline, especially in very rich, high-TOC shales.

The interplay becomes even more critical when considering advanced stimulation and recovery technologies. For example, the use of supercritical CO_2 as a fracturing fluid has been proposed as a water-free alternative that could also initiate EGR from the outset [1]. However, the significant swelling induced by CO_2 [5] must be carefully managed to ensure that the created fractures remain conductive. Similarly, other innovative fracturing techniques, such as those using low-temperature fluids [13], plasma-based methods [2], or foam-based fluids [3], will all interact with the reservoir's geomechanical state in unique ways. The success of these technologies will depend on a thorough understanding of how they alter the stress field and interact with the rock matrix. The coupled simulation studies by Jiang & Yang [14] and Kudapa et al. [17] highlight that it is only by considering these integrated effects that a realistic picture of reservoir behavior can be obtained.

DISCUSSION

Interpretation of the Coupled Mechanisms

The evidence synthesized in this review points to an unequivocal conclusion: in shale reservoirs, mechanical processes and fluid flow are profoundly and inseparably coupled. The traditional approach of treating permeability as a static petrophysical property is fundamentally flawed. Instead, permeability must be viewed as a dynamic variable that evolves in response to the changing stress and chemical environment of the reservoir. The interplay between stress-induced compaction and sorption-induced strain creates a complex feedback loop. Pore pressure reduction increases effective stress, which reduces permeability; this, in turn, slows down pressure propagation and alters the production profile. Simultaneously, the pressure reduction causes desorption and matrix shrinkage, which slightly counteracts the stress effect. Treating these mechanisms in isolation—for example, by using a stress-sensitive permeability model but ignoring sorption effects, or vice versa—will lead to an incomplete and likely inaccurate representation of reservoir behavior and, consequently, flawed production forecasts and suboptimal field development strategies. The true behavior emerges from the continuous, dynamic competition between these phenomena.

Implications for Hydraulic Fracturing and Reservoir Management

A deep understanding of these stress-strain dynamics has significant practical implications for the entire lifecycle of a shale gas well. During the initial stimulation phase, this knowledge can inform the design of hydraulic fracturing treatments. For instance, recognizing the severe impact of stress on fracture conductivity underscores the critical importance of effective proppant placement to keep fractures open. The choice of fracturing fluid is also crucial. The potential for CO_2 to be used as a fracturing fluid is intriguing, as it could eliminate water usage and store carbon [1, 22]. However, the significant matrix swelling it induces [5] presents a major challenge that must be overcome, perhaps through cyclic injection strategies or the use of chemical additives that mitigate swelling. Other novel fracturing methods, such as abrasive gas jets [21] or those based on spontaneous imbibition [25], also need to be evaluated within a robust geomechanical framework.

For long-term reservoir management, this understanding is essential for optimizing well spacing and predicting well interference. It is also paramount for designing and evaluating EGR projects. The feasibility of CO_2-EGR, for example, hinges on balancing its superior displacement efficiency with its detrimental swelling effect [28]. Coupled models are the only tools capable of performing this complex optimization.

Knowledge Gaps and Future Research Directions

Despite significant progress, several knowledge gaps remain. First, there is a pressing need for more sophisticated, fully coupled, three-dimensional reservoir models. Many current models are two-dimensional or simplify the complex fracture geometries. Developing robust 3D models that can handle complex, non-planar fracture networks and integrate the full suite of geomechanical effects is a major computational challenge but is essential for accurately modeling horizontal wells.

Second, there is a need for more high-quality experimental data. Specifically, more experiments are required to measure the mechanical and flow properties of diverse shale types under true triaxial stress conditions that mimic the in-situ stress anisotropy. Most existing data comes from simpler uniaxial or hydrostatic tests. Furthermore, more research is needed on the long-term evolution of fracture networks under the cyclic stress conditions that might be experienced during refracturing or cyclic gas injection schemes.

Finally, the integration of different novel stimulation technologies within this coupled geomechanical framework is still in its infancy. The potential benefits and drawbacks of techniques involving cryogenic fluids [13], plasma [2], or advanced fluids like foam [3] are not yet fully understood from a geomechanical perspective. Future research should focus on integrating these new physics into the existing coupled modeling frameworks to provide a more holistic assessment of their potential.

CONCLUSION

Summary of Findings

This review has synthesized the extensive body of research demonstrating that stress and strain are not passive parameters but are active, dynamic agents that fundamentally modulate the permeability and gas production potential of shale reservoirs. The evidence confirms two primary, co-existing mechanisms. First, the permeability of the essential fracture network is highly sensitive to effective stress, leading to significant conductivity loss as reservoir pressure is depleted. Second, the physicochemical interaction between reservoir gases and the organic-rich shale matrix induces substantial strain in the form of swelling or shrinkage. This sorption-induced deformation directly alters fracture apertures, acting as a secondary control on permeability. The long-term performance of a shale gas well is dictated by the complex, time-dependent interplay between these competing geomechanical effects.

Concluding Remarks

The era of treating shale reservoirs as simple, rigid systems is over. The future of efficient and sustainable unconventional resource development lies in embracing their complexity. Incorporating dynamic, coupled stress-strain dynamics into reservoir simulation and management workflows is no longer an academic exercise but a practical necessity. By doing so, the industry can move towards more accurate production forecasting, the optimization of hydraulic fracturing and well spacing designs, and the intelligent development of next-generation enhanced gas recovery strategies. Ultimately, a deep and integrated understanding of geomechanics is essential for unlocking the full economic and strategic potential of the world's vast unconventional gas resources.

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