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Geomechanics and Material Performance in Unconventional Reservoirs

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Abstract
Increased focus on unconventional oil and gas, such as shale, coal-bed methane, and hydrates, has introduced the industry to new and often significant challenges. In many cases, the operational expenditures for these unconventional resource plays have been higher than classical recovery and have shown poor recovery factors. A foundational component, which must be understood in order to overcome these operational barriers, is the behavior of the geological formations to the extraction processes. Geomechanical principles aim to capture and understand the extractive forces and behaviors that exist in the pressure, temperature, salinity, mechanical properties of the components present, time and spatial distribution, and geometries of wells. Two primary operational parameters of interest that are linked to the formation type and size-geometric distribution and scale of well construction related to the rock/pore-fluid material properties at the interface. Some of the latest research into the relationships between the formation material characteristics and material performance during unconventional resource recovery. Geomechanical formation interfaces are both characterized by being low-porosity, low-permeability systems in which production can be challenging. In addition, while mineralogy may largely differ, the compressibility and mechanical strength behave in a common manner, as does the creep performance in the application of stress. Respective geomechanical implications are analyzed. Thus, as exploration of natural unconventional resources grows ever more to lower porosity and greater depths, wells operate with increasing concern for the hydraulic barrier focus, which is perceived and verified by the larger, non-linear increase in operational pressure compared to the linear time rate of pressure decrease. The by-product of this issue is unauthorized formation damage as a systemically growing conundrum, where maintenance, workovers, and subsequent hydraulic focus come with a cost in economic viability. Simultaneously, these areas are turning to the development and/or integration of enhanced recovery techniques increasingly from a mechanical perspective and holistic economic benefits versus traditional methods.

Keywords: *Geomechanics Material performance, Unconventional reservoirs. Geology Geological engineering, Materials science, Interface, Hydraulic fracturing, Frack hits Stimulation-failure, susceptibility Rock properties*

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I. Introduction to Geomechanics and Material Performance

Geomechanics, the study of material behavior and its response to physical and mechanical loads and boundary conditions (Hawez et al., 2021; Houhou & Laloui, 2022), has gained significant prominence in recent decades, particularly in the context of unconventional reservoirs. As the energy industry shifts towards more complex geological systems, understanding the mechanical behavior of reservoir materials becomes crucial to address challenges in production and fluid injection (Rezaei et al., 2020). Thus, the scientific discipline of geomechanics has developed initially as an interdisciplinary science, which synthesis is based on three branches of knowledge which are the physical and chemical as well as the geotechnical sciences. Previously, its uses were mostly associated with simple cases of surface mining and tunneling especially in relation to toolhole conditions. However, with the growing need for exploration and production of hydrocarbons, geomechanics also operates at both sub-surface and at the surface.

Actually, scientific discipline connected with study and analysis of the geomechanical circumstances in the toolhole has developed beyond the mid-20th century and includes a range of intricate underlying rock and material characteristics. A high level of appreciation of how rocks respond to stress and the behavior of fluids within the porous media, rock mechanical properties, and the materials applied during drilling and extraction and storage are crucial. To sort out these puzzling issues, synergy between academic, pragmatic professionals, and practitioners is inevitable.

Definition and Scope of Geomechanics

Geomechanics which is the study of mechanical and hydraulic properties of rocks and soils (Hawez et al., 2021; Cai et al., 2021) is important in predicting the behavior of unconventional reservoirs. At present, laboratory tests, field measurements, and theoretical analysis to define the mechanical response of these materials under these stresses are possible (Shen et al., 2022; Masouleh et al., 2020). Generally, geomechanics aims at analyzing subsurface reactions in response to changes caused by drilling, hydraulic fracturing or/and production (Rezaei et al., 2020). This understanding is critical in the conceptualization of hydraulically fractured reservoirs as well as in enhancement of production plans. Mechanical properties, stress conditions, and material response constitute the highlights in geomechanics. Geomechanics has importance for drilling, hydrocarbon production, well bore stability, hydraulic fracturing, and proppant-propped fracture. Furthermore, a part of geomechanics includes applying knowledge of various natural geological processes. Much work has been done on the quantitative description of the mechanical properties of rock material and strength parameters that could be obtained from laboratory and field testing (Sangnimnuan et al., 2021; Liao et al., 2024), however, the further studies are necessary to investigate the influence of the fracture and formation configurations on the rock behaviour under various geologic conditions.

Geomechanics can therefore be described as the study upon which predictions regarding the behavior of formations in a given subterranean geography can be based. Geomechanics applies experimental, theoretical, and numerical model raising innovative and effective technologies to extract energy sources that can be considered as sustainable.

Significance of Geomechanics in Unconventional Reservoirs

Geomechanics has attracted much attention in the development of the unconventional oil and gas resources, many of which are in complex structural conditions including faults (Rezaei et al., 2020). These reservoirs can be characterized in terms of their geomechanical features which affect fluid behavior and output. The problem of the low permeability and porosity of the shale rocks results in low productivity of the reservoir and low permeability forcing the need to apply highly complex technologies such as hydraulic fracturing to raise the reservoir permeability (Hawez et al., 2021). Good knowledge of the stress regime and rock properties become vital in managing Wellbore stability in such hostile regions (Yan et al., 2020). A well-known stimulation method used is hydraulic fracturing that employs a contact between the injected liquid and the formation. Dependence of this technique is typically with the characteristics of the rock; stress regime and nature of the fluid being indicated. The current studies have shifted focus towards analysis of the cooperation between natural and artificial materials especially in relation to stress distribution and the future behaviour of reservoir systems (Houhou & Laloui, 2022). Alterations and damages within the rock matrix, at a microscopic level, may affect the different aspects of fluid flow and production. Furthermore, the effect of geological parameters on reservoir dynamics is crucial to improve the productivity plans (Kuang et al., 2023; Xu et al., 2022; Cai et al. 2021). Reservoir simulation utilizing geomechanical fundamentals is an effective way to enhance the representation of reservoir behavior and improve decision making on production. According to this type of integrated approach, resources can be recovered better and the environmental effects can be minimized.

Mechanical Properties of Rocks in Unconventional Reservoirs

Knowledge of the mechanical properties of rock is crucial in the build-up of the unconventional resource outcomes due to the creation of porosity and permeability through stressing the reservoir rock (Tiab & Donaldson, 2024). Certain properties of the materials under study that has a significance to the researchers are brittleness index, fracture toughness and unconfined compressive strength. Brittleness is a crucial property for understanding the propagation of fractures in reservoir rocks. The greater the brittleness of a reservoir rock, the more likely fractures will propagate when hydrocarbons are extracted. Fractures can also be created with hydraulic fracturing technology if sufficient fluid pressure is applied. Consequently, this technology is effective only in reservoirs that contain more brittle rock. Most research suggests that the addition of more proppant increases conductivity to such an extent that the largest fractures produced by changes in a reservoir's brittleness index will not significantly affect the flow inside the fracture (or in the reservoir around it) (Ganguli & Dimri, 2023).

The fracture toughness of reservoir rocks is essential because it can help determine when fractures will stop growing (Zhuang et al., 2022). Understanding the toughness of a fracture can be crucial to either stopping fractures from propagating outside the rock, potentially causing lost production because the rock has become worse at producing hydrocarbons, or allowing the fractures to continue growing, which can also affect hydrocarbon production. The fracture toughness of the rocks must be considered in addition to understanding forces and pressures. These three parameters of rock composition, structure, and mechanical behavior cannot be developed through a review of the literature and should require an assessment of the rocks in question. Consequently, the response of the reservoir to the development strategy that an engineer might develop is also questionable. Although this is beyond the current scope of engineering applications, it is important to remember that there is a great deal of research occurring in this area (Liu et al., 2023).

Brittleness and Its Role in Hydraulic Fracturing

Brittleness is defined as the lack of malleability, or more fundamentally, the ability to deform without rupture (Wu et al., 2024). Commonly, it is quantified as the ratio of the uniaxial compressive strength to the tensile strength (Yan et al., 2024). Recent advances in geomechanics, however, have considered a number of more relevant definitions in the context of hydraulic fracturing (Li, 2022).

Brittleness is known as the fundamental factor influencing hydraulic fracturing and the performance of the whole multi-stage fracturing process (Zeng et al., 2023). It affects when, where, and what kind of rock fractures are generated, as well as the propagating trajectory and responding energy accumulation (Temizel et al., 2022). It also influences the fracture width and fracture conductivity during the production stage (Zou et al., 2020).

In terms of quantity, mathematic values are used such as the brittleness index which varies in between ductile 0 and brittle 1(Hussain et al., 2023). In practice, there are some kinds of brittleness indexes calculated from the physical features. Many of these will be employed in directing the process of designing and executing hydraulic fracturing: designing the fracturing pattern to build improved fractures; defining what types of proppant to use in efficiency-making; and the like (Kolawole et al., 2020).

I’d like now to explain what kind of changes brittleness allows one to trace by providing an example of hypothetical experiments. For instance, let the rock sample you are working with be very brittle, its brittleness index being, therefore, nearly 1. Thus, when you apply hydraulic fracturing to this rock, the fracture extension is more likely to happen in a manner you want them to and they create wider more well-connected channels whereby free flowage of hydrocarbon may take place. On the other hand a ductile rock with a relatively low value of brittleness index lower than 0 might appear with the narrow and less permeable defects and hence the hydraulic fracturing operation may not be effective.

The ability to characterize and measure the brittleness of the reservoir rocks is imperative when evaluating the hydraulic fracturing processes. This work produced the necessary understanding that by choosing the most suitable brittleness index and aligning the fracturing parameters correspondingly, it is possible to achieve the optimal productivity and effectiveness rate of hydrocarbon production (Lawal et al., 2021). This knowledge assists in closing the gap from the inherent geomechanical properties of the rock and the applicability of hydraulic fracturing technology.

Application in unconventional reservoirs

While transitioning to the types of reservoirs, which are considered to be unconventional, brittleness is the feature that is more significant (Li, 2022). One of the significant problems when estimating can be the assessment of the relevant parameters and the analysis of how they influence the physical behaviour in general (Wu et al., 2023). So, what are the geological factors that will dominate the brittleness of rock? The distribution of clay minerals or the maturity of quartz in a shale gas well can have a direct effect on the brittleness of the rock (Liu et al., 2020). This means that the lithological composition and diagenetic history of the reservoir rock can significantly influence its brittleness characteristics. At the same time, what operational parameters should be included in the indexes of brittleness? From our previous experiences, the possible number of fracturing stages in the "sweet spot region" may be limited due to the brittleness of the rock (Sun et al., 2021). As a result, an evaluation of the brittleness may be a primary principle for guiding the development well design, especially with the consideration of large-scale hydraulic fracturing (Meng et al., 2021). Are these geological and operational factors irrelevant for the unconventional wells? Not necessarily. They may have more to proceed for the detailed debate and exploration of how rock characteristics, reservoir conditions, and fracturing methods can interact in geomechanics contexts among themselves and with others still today in the sphere of unconventional resources (Iranfar et al., 2023).

For instance, the clay mineral type and quartzaturity that defines brittleness can be vary greatly in the shale, tight sand or coal seam reservoir (Li et al., 2020). Likewise, the number of fracturing stages to be employed and their location can be best identified based on the brittleness properties of the particular unconventional resource type (Kumari & Mohan, 2021). Finally, it can be stated that acquiring an extensive knowledge of brittleness in unconventional reservoirs is accomplished by means of a systemic and synthesized approach. It involves the study of the geological factors, integrating the effective operational parameters and the framework of the suitable assessment approaches while considering the characteristics of these complicated geological systems (Lyu & Lu, 2024). In this way, it is possible to address the challenges of fracturing design and enhance the general performance of acquiring hydrocarbons from the unconventional reservoirs (Alneasan & Alzo’ubi, 2022).

Fracture Toughness and Reservoir Stability

The first is the specific fracture toughness, which represents the crack formation and growth resistance of the material when a flaw or fracture exist, and is the most desired parameter to be evaluated during any process of rock fracturing (Ritchie, 2021). If the material can get a sufficiently high value of fracture toughness, then the fracturing process can occur with some measure of control over the process (Gdoutos, 2020). The actual ASR site characterization-derived quantity of fracture toughness, though, can vary rather dramatically based on rock type and orientation, according to other sources (Sharafi et al., 2021). It must be larger than some critical value in order to avoid buckling or failure of the system (Shaikeea et al., 2022). It is here that highly complex and demanding geomechanical methods often end up being the best means by which to identify the true behavior of the rock (Long et al., 2021).

Let us go through an example in order to gain a clearer insight into why fracture toughness is so significant. For instance, let’s assume that you have a shale reservoir in your possession and you wanted to use the technique of hydraulic fracturing. The behaviour of the shale and the initiation of the fracture will be critical in achieving the desired propagation of the fractures which will determine its stability in the future (Molnár et al., 2020). Vigorous stresses at depths having high fracture toughness can actually capture the fracture growth, and in turn the performance of the well may be slightly impaired (Wondraczek et al., 2022). On the other hand, if the shale has low fracture toughness, the fractures can continue to extend leading to problems with wellbore stability or induced seismicity (Lew et al., 2021).

When it comes to the fracturing process, to generate the best results, the fracture toughness of the shale has to be measured and analyzed to allow the fracturing design and operations to exactly fit the outcomes. This knowledge also assists in determining well pad locations, and can direct the general development plan of the unconventional reservoir (Hu et al., 2020). The current research indicates that several years of research and studies are still needed before the precise connection between hydrocarbon migration/accumulation within slates and fracture toughness is established (Tao et al., 2024).One important area where the fracture toughness analysis would be particularly beneficial is in the location of well pads particularly where extremely high reservoir complexity makes full appraisal before onset of the drilling program impossible (Gao et al., 2024). Through the application of fracturability analyses as well as follow-on analyses to ascertain if fracture toughness will be exceeded at likely fracturing sites, failures can be avoided at costs that are far less than for the stimulation methods (Luo et al., 2020).

Hydraulic Fracturing (Fracking) in Unconventional Reservoirs

Predicting the flow mechanics is of paramount importance concerning all issues in hitherto literatures regarding the flow in the unconventional reserves (Birkholzer et al., 2021). Thus, the attempts to create the engineered pathways for flow have resulted in the technology known as hydraulic fracturing, which is the process whereby engineered fractures and cracks are created in a volume of rock in order to stimulate production of gas, water or oil to the surface of the ground (Jew et al., 2022). We henceforth use the term “hydraulic fracture” intentionally shorter as ‘fracking’. Let's break down the steps involved in the fracking process: Well, extended to target the reservoir section (Aboagye, 2022)., Pump high pressure to the rock in an attempt to create a fracture (Liu et al., 2021).,Open and propagate this fracture until the rock is sufficiently stimulated (Guo et al., 2020).,Inject proppant into the open fracture to further keep the rock open for flow (Gupta et al., 2021).In essence, hydraulic fracturing involves moving a rock formation from a state of zero porosity and zero permeability, where there is little or no potential for mass flow, to a porous medium with high porosity and high permeability, with a potential for gas to flow, easily mobilizing a massive amount of fluid already present in these rocks (Qun et al., 2022). Fracking, therefore, happens at the intersection of flow and mechanical considerations and advanced reservoir management systems (Kalam et al., 2021). Many factors such as rock properties, fluid properties, and pressure constraints under which fluid injection or injected fluid interacts with the in-situ fluid stored in the rock formation all impinge upon the fracture formation and the ultimate recovery from unconventional reservoirs (Zhuang & Zang, 2021). Fracking, given the right rock and fluid conditions, could liberate a massive number of natural resources and is the best-known process for resource extraction (Varzaneh et al., 2021). We share the belief that while fracking is a key endeavor within geomechanics, as indeed is rock-mass flow and hydraulic fracturing in any type of medium, it indisputably lies at the interface of an array of sciences (Wu et al., 2022). The flow of fluids in reservoirs seen by petroleum engineers is therefore about as relevant as the displacements of 'shale' blocks in reservoirs, seen by the physicist (Li et al., 2021). Overall, hydraulic fracturing serves a vital purpose of producing resources from unconventional reservoir formations (Zhuang et al., 2020). It is a complex process that requires a deep understanding of the interplay between fluid dynamics, rock mechanics, and reservoir engineering principles (Tomac & Gutierrez, 2020). By carefully considering these multidisciplinary factors, engineers can optimize the fracking process and maximize the recovery of valuable hydrocarbons from challenging unconventional reservoirs (Viswanathan et al., 2022). To further illustrate the importance of this topic, let's consider a hypothetical scenario. Imagine you have a tight shale formation with extremely low permeability. Without fracking, the shale would be essentially impermeable, and extracting the trapped natural gas would be nearly impossible (Noiriel & Soulaine, 2021). However, by applying the principles of hydraulic fracturing, you can create a network of high-conductivity fractures that allow the gas to flow much more freely to the wellbore (Fazio et al., 2021). This opens up the prospect of the high risk AVB and ensures that the development of the unconventional reservoir is commercially viable (Ladd & Szymczak, 2021).

Process Overview

These include natural gas, oil and geothermal reservoir resources trapped in deep, low permeability, low porosity rock types like shales, sand, coal and carbonate (Tolmachev et al., 2020). The low permeability prevents the migration of fluid within the reservoir rock, while the low porosity tends to limit the volume of resource fluid in place (Pang et al., 2021). It is extremely difficult to move this slow-diffusing fluid from the reservoir pores to the drill wellbore intersecting the reservoir rock. As a result, geophysical logs often identify zones where hydrocarbons may be concentrated but are low in volume (Li et al., 2021). To facilitate resource flow from unconventional reservoirs to the wellbore, a complex process called hydraulic fracturing is used, high-pressure treatment of a wellbore with high-velocity fluids or solids to create fractures in the rock (Canbaz et al., 2020). Hydraulic fracturing involves several distinct energy transfer phases, each with their own operational mechanisms (Gharavi et al., 2023). Wellbore preparation, including geomechanical survey technologies and drilling. Hydraulic and mechanical conditions used to control and induce the formation of the fracture and proppant transport. Monitoring of the operation for real-time decision making, including well test tools. The effectiveness of hydraulic fracturing is closely tied to the rock condition in terms of modulus, stress, rock types, and other properties (Bera & Shah, 2021). Documentation and field operations should be conducted on the production ranges of porosity, pore size, permeability, stress condition, and damage conditions. Several studies have investigated the relationship between the geological properties acquired through engineering tools, such as porosity, density, and Young's Modulus, and fracture propagation, operation pressures, and operational economic ranges (Song et al., 2021). By establishing this relationship between rock geology and the desired stimulation designs, field operation engineers can design programs for maximum increased reservoir flowback to the operator. It's important to also consider the advantages and disadvantages of various stimulation techniques, as well as the basic operational problems and difficulties regarding fracture creation and formation (Lai et al., 2022). This includes issues related to geomechanical instability, placement, and proppant, as well as the logistical and operational challenges involved with well stimulation. To illustrate this concept further, let's consider a hypothetical scenario. Imagine you have a tight sandstone formation with extremely low permeability, similar to the shale formations we discussed earlier. Without hydraulic fracturing, extracting the trapped oil or gas would be nearly impossible, as the fluid would have a very difficult time flowing through the tight rock pores to the wellbore. However, by applying the principles of hydraulic fracturing, you can create a network of high-conductivity fractures that allow the fluid to flow much more freely to the wellbore. This increases the permeability of the unconventional reservoir and brings the development of the reservoir within the economic range. The specifics of how it was to be done, the type of fracturing fluid to be used, the type of proppants to be included and the pumping pressures to be applied in the formation of the sandstone network would be decided bearing in mind the particular features of the formation. This paper presents an overview of the rock properties, the mechanisms of fluid flow within the reservoir, and the opex considerations that allow engineering professionals to develop optimized strategies for hydraulic fracturing that unlocks the potential of available, yet challenging, unconventional energy resources. Geothermal exploration is a demanding yet crucial drive for fulfilling the increasing global demand for oil, gases, and many more.

Geomechanical Considerations in Fracturing Design

Unconventional reservoirs, however, do not allow for the determination of the exact geomechanical parameters and in-situ stress states at each location but a fair spectrum of fracturing or other geomechanical properties can be gained from information provided by drilling programs along with optimum geomechanical characterizations (Fraser et al., 2021). From these properties useful information which could be used in the design of hydraulic fracturing operations is obtained. The properties of the rock and the condition of the reservoir can directly impact the pressure needed to open fractures in the rock and also how it is stressed in-situ and any faults are present (Li et al., 2022). Other newer technologies such as microseismic monitoring can also be used to gain information that relates to the geomechanical characteristics of the reservoir (Yong et al., 2022). This includes information about the response of the newly created fracture network with the existing natural fractures in the formation. Because rock properties depend on the geological location of the field, carrying out a detailed investigation of rock properties in each field is crucial (Pham et al., 2020). An accurate knowledge of the rock properties and existing conditions are yardsticks in managing the geomechanical behaviour during the hydraulic fracturing treatment (Xu et al., 2022). This integration of geomechanical analysis makes sure that some fails that may occur due to stresses that would be unmanageable during the operations do not occur in the well bore. In order to better explain this concept, we will think of a situation. Suppose you are planning a hydraulic fracturing treatment for a shale reservoir in the Haynesville play within Louisiana and Texas (Zhang et al., 2023). Namely, the further development of an effective fracturing design in this area importantly requires the integration of different approaches. The first step would be to undertake tri-axial on some cores in order to predict the anisotropic stress parameters prior to the fracture (Tuzingila et al., 2024). Furthermore, applying the well log data, you would calculate the fracture gradients and the formation breakdown gradients for the region (Sundli et al., 2024). This would afford a detailed geomechanical evaluation to assist you to determine the correct fracturing parameters including pump pressures and volumes to complete the treatment.

In addition, microseismic technology as described earlier could be applied for further monitoring of the interactions between the engineered fractures and any inherent geological features in the shape of natural discontinuities in the shallow formations (Hawez et al., 2021). This would enable you to adjust the type of fracturing design and also make changes on the job to optimize the results of the treatment. By integrating these various geomechanical analysis techniques, you can develop a deeper understanding of the subsurface behavior in the area of interest. This, in turn, enables you to make more informed decisions on well site selection, hydraulic fracture design, and mitigation of wellbore instability risks. The goal is to ultimately maximize the drilling, development, production, and hydrocarbon recovery from this challenging unconventional reservoir.

Materials Science in Unconventional Reservoirs

The materials science and engineering in the context of unconventional reservoirs, or shales, bears a very close resemblance to the intertwined science of geomechanics. Critical engineering materials have always mediated the interactions between the extracted hydrocarbons, surface reservoir equipment, and the subsurface geological formation of interest. To an extent that far exceeds traditional reservoirs, these interactions are very close to the desired unconventional resource and recovery process. Furthermore, the need to present a subsurface geological formation capable of storing and generating extractable hydrocarbons that will facilitate their movements and extractions to an adjacent initiatory well also demands massive amounts of such materials (Bratton, 2025). Thus, it is time to view these materials not as a necessary evil to be cheaply bought and logged on haphazard goodwill but as thoroughly selected and tested advanced engineering materials designed and performed for a specific application (Guo, 2024). This is as exploration of novel engineered materials such as advanced hydraulic fracturing and other enhanced recovery techniques becomes the cutting edge for our economic and environmentally sustainable extraction optimization toolkit (Kuang et al., 2023). Materials are a class of engineering material that is custom designed to optimize a geologic process or economic indicator. Applications already strongly involving material science include engineered proppants, drillable/dissolvable plugs, and even self-healing cements (Karvinen & Kellomäki, 2023). Interactions with the formation at different depths are a key parameter to be optimized in addition to traditional engineering material characteristics. Material selection is dictated by the formation since key properties such as minimum tensile failure and chemical stability translate to improved fracture and well longevity (Ye et al., 2023). Environmental and cost impacts are also key characteristics as oil and gas extraction becomes more focused on safety and sustainability (Suslick et al., 2023). While examples of successful applications do exist in practice, the vast majority of work remains as proofs of concept rather than commercial technologies (Das et al., 2023). This discussion will focus on several examples of how material selection relies heavily on interaction with the formation and practical impacts of sequestration on energy sustainability and infrastructure, focusing on recent case studies and real-world work (Palacios et al., 2023).

Engineering Materials for Enhanced Recovery

Materials can be selected and designed to engineer a response to enhance resource recovery. Several kinds of materials are being used in hydraulic fracturing operations, from closure materials such as degradable plug materials to fluid-based additives such as friction reducers. These engineered materials often hold a function beyond simply maintaining a permeable connection. It is expected that significant savings in cost and environmental impact will occur by optimizing material properties based on particular reservoir constraints, including subsurface permeability, reservoir confinement, and the chemical composition of native brines (Zhao et al., 2022). By engineering the constituent materials within a fracture, an operator can directly influence production mechanisms such as in situ stress change, fluid rheology, proppant embedment, conductivity, and enhanced recovery. In this respect, engineered materials also directly influence fracturing efficiency and thus hydraulically fractured volumes and beyond. Smart materials represent the most advanced development in material technology that can be engineered to exhibit specialized behavior to induce a response such as enhanced recovery (Wu et al., 2022). The geomechanical response of unconventional rock to the engineered materials is often integral in the decision-making process. The success of material selection is often based on the well-to-well hydraulic fracturing performance of specific rock properties, from between the 'sweet' and 'fat' tails of an in-situ stress gradient to host and local geologies (Huang et al., 2024).

While the static and dynamic strength of materials are essential in determining their compatibility to displacement, the experimental design and optimization of the material composition are now better understood through the application of mineralogy, rock sampling, and imaging (Xiong & Ma, 2022). As a mature field, a systematic approach to marrying material properties with production has been suggested through the standardization of computational material science within full-scale reservoir simulation and production optimization (Phoon et al., 2022). Compliance with performance-based targets can be more difficult in areas of exploration and in-situ monitoring where fluids, stresses, and dissipation behavior are less understood (Li et al., 2024). The scaling down of material behavior as a function of grain size and the compatibility of materials with reservoir inclusions is still an active area (Xiao et al., 2024). This decoupling of material performance from microstructural constraints is essential for the future development of materials capable of both closure and high-permeability emission in the gas extraction industry (Cai et al., 2021).

Interaction of Engineered Materials with Geology

The natural matrix in unconventional reservoirs (porous or naturally fractured) can be shown to govern the performance of engineered materials. The permeability of engineered proppants in the natural matrix can be quite different from what is measured in standard laboratory scale due to diverging morphologies at different scales or self-sustaining fracture initiation and propagation resulting in a fractal continuum. Permeability modifiers or swelling agents can be used to selectively keep gas-tight induced fractures rather than the propped fracture, and fracture toughness agents need to alter the mechanical behavior of the natural matrix, into which they can potentially diffuse (Ramazanov et al., 2024). For sizing particles, the interdigitation and corruption of pores and flaws also result in a deviation from the universal Weibull statistics that apply to fully dense or concentrating statistically non-interacting defects (Fan et al., 2020). If a hydraulic fracture grows in less mechanically competent layers of the same stratigraphy clays, Albian, Cretaceous limestone, Cretaceous dolomite, the hydraulic fracture growth resistance is expected to decrease proportional to the ratio of material preserving resistance of the more competent layer to the pressure messages induced by pressurizing it with millions of cubic meters of fluid (Ramlan et al., 2021).

Interactions between natural and engineered materials downhole can be prevented by quiescing the gas production or by sealing the annulus (Danso et al., 2021). Evaluation of the chemistry of these reactions can be performed on site to prevent losses due to an exothermic reaction within a blowout preventer with announced storage limits (Katende et al., 2021). Successful injection of engineered materials can also weaken the integrity of the wellbore with an impact on other completions and drilling operations. This list is by no means exhaustive because new mineralogy, demography, and permeability could be formed during subsurface reactions and interactions (Bandara et al., 2021). Fracture optimization must be conducted contemporaneously with drilling execution to maximize well integrity, recovery, and completion costs without inducing geohazards (Tasqué et al., 2021). However, these unforeseen interactions between engineering materials in general and hydraulic fracturing in particular, and natural formations are associated with physical aspects that can be mitigated to an extent through material design and pre- or post-processing testing (Zhang et al., 2022). Beyond the engineering, petrophysical, and geophysical techniques that have been used in the past to take corrective action based on observed unexpected interactions among engineered and natural formations, only a geological assessment of the potential relative reactivities has the potential for a certain in-situ prediction of the outcome of the compatibility/incompatibility at the engineering scale (Al et al., 2024). Integration of these disciplines creates the new paradigm of material engineering, material science, and geological compatibility in-situ assessment.

Designing Effective Extraction Techniques

This paper is aimed at delivering an improved understanding of existing strategies, suggesting the use of existing concepts in combination with new ones, and helping in developing more effective and robust techniques for extracting fluids from unconventional plays. The design of effective extraction techniques is perhaps the most significant activity to be performed in the field of petroleum engineering to facilitate the production of fluids from unconventional reservoirs. Hence, considerable efforts at the planning stage are spent trying to optimize the propagation of the fracture network within the rock. Several displacement mechanisms can be invoked to assist in the recovery of fluids in these rocks.

However, the eventual choice of permitting mechanisms requires careful consideration of factors such as reservoir conditions and the type of reservoir, impact on extraction and injection, and efficiency in terms of recovery and potential risks (Shen et al., 2022). Chargeability design and monitoring in real-time can be studied to determine the preferred conditions (Ozowe et al., 2024).

The resulting design parameters and associated operational limits are then evaluated in terms of the buckets of the surge, including available technology. A further discussion can also be made for drilling in variable geological settings, given the wide variation in equipment and operating procedures that need to be developed effectively (Kurade et al., 2021). Finally, the paper explains the need for the assessment of geomechanical activities in an unconventional plan to develop an effective extraction strategy. Reducing the separation of wells and, hence, the creation of connected fracture networks may be achieved by adopting operational procedures to induce changes in the stress profile along the wellbore.

Optimizing Fracture Network Propagation

One of the key components of the unconventional recovery process is the optimization of fracture network propagation in reservoirs. Over the past decade, there has been significant progress in understanding and designing fracture propagation with the aim of substantially increasing fracture connectivity, and hence oil and gas recovery. A properly designed hydraulic fracture network may maximize fluid flow and enhance the rate at which resources can be recovered. To optimize the flow field in the reservoir, operators need a well-designed propped reservoir area. There are several ways to optimize the fracture network, including the adjustment of the spacing or fracturing orientation; these work as powerful tools to increase the connectivity between the different fractures that can propagate (Huang et al., 2021).

There are three potential methods to predict and optimize fracture propagation: the first one is based on an image log, on the natural discontinuities, then a physical model is realized. The model is either a synthetic or a transparent block that will be fractured in different azimuths and inclinations to detect the potential best geometry to propagate and link fractures. The second one is based on analytical models that will describe theoretically the fracture propagation in the rock for a given formation and in situ stresses. The third one is a numerical model, it will simulate the fracturing of the rock for a given formation and in situ stress. Once developed, the model can indicate the propagated length, the length of the connected fractures, the fracture orientation, and potential failure. In addition, it can also calculate the fractures' spacing or the variance in azimuth and height between the different fractures. Thus, the predicted fracture model can then be used during the hydraulic fracturing process (Xu et al., 2023).

In general, the design of the fracture network is tailored to the specific stresses and fracturability of the rock. The in-situ stresses in the area of investigation play a major influence in the design proposed. When considering the complexity of the subsurface reservoirs, or potentially those that are quite heterogeneous, the design needs to take into account the variability of the rock properties so the designed fracture network remains optimal. It is important to conduct these studies early in order to avoid damaging the induced fracture network and optimize network fracture connectivity proactively (Gao et al., 2024).

Minimizing Operational Risks Hydraulic fracturing in unconventional reservoirs can lead to equipment failures, which can have catastrophic, long-lived consequences. Several risk analyses focus on one or a mixture of a few factors, tending to find that operational problems are primarily due to mechanical issues rather than geological uncertainties. It is commonly estimated that between 5% and 10% of recently drilled wells might require sidetracking, and perhaps as many as one in a thousand wells drilled for hydrocarbon extraction will need to be abandoned. The relative failure rate for sidetracking is higher over a retrospective 10 to 20-year period, suggesting that modernized approaches may have mitigated this concern somewhat. Hence, focused designs for risks prevailing in a particular environment or operational setup are necessary (Ismayilov & Mahmudov, 2024). Risk assessment involving the drilling and operation of shale wells should be based on the reservoir-specific site conditions as the complexity varies drastically from one shale to another due to different mineral compositions, brittleness indices, and hydraulic properties.

Dedicated risk assessment methodologies for short-term operational problems in newly exploited unconventional dual-porosity systems can identify operational and performance challenges at an early stage, preventing labor- and time-intensive deliberation stages (Willerth et al., 2022). Strategies to mitigate the operational risks in such cases primarily involve preventive measures through planning, drilling, and completion engineering solutions, as well as operational and surveillance requirements to be implemented on the site (Pedrote et al., 2024).

Given the complexity of unconventional reservoirs, in-house production has provided evidence and highlighted the benefits of adaptive management in real-time operations due to development or early surprises (Emelander, 2022). Furthermore, a few case studies from successful hydraulic fracturing procedures in unconventional systems could provide insights from practical implementation. The impact of these operational failures on public perception, affecting a shift from an operational risk to an essential environmental concern, must also be a motivation. Hence, risk management strategies for operational inefficiencies require a comprehensive outreach to various stakeholders, and the importance of satisfying stakeholders' needs from an unconventional material performance perspective can be captured (Amra, 2024). Ensuring compliance with regulations, no matter how complex the system, is also of utmost importance. The role of regulatory bodies, which contribute to minimizing operational risks in unconventional projects by reliance on management procedures and safety cases that fully demonstrate that risks can be controlled, must be emphasized herein (Fathi et al., 2023).

II. Conclusion

This paper has presented the overview of different aspects of the interactions between geomechanics and material performance in unconventional reservoirs. Integrated geomechanics in extraction processes can lead and is leading to recovery enhancements and stability improvements of these reserves. Different aspects of the ‘material’ have been explored. This includes its mechanical properties, the multi-physical mechanisms that govern flow, and coupling, e.g., poromechanical behaviors such as plasticity, and changes in permeability. Hydraulic fracturing, yet another important aspect of these reservoirs as an extraction process, is also attempted to be treated as an interconnected and not isolated process. The effects of the rock’s material properties on hydraulic fracturing, the amount of energy deposited and the fracture network formed have been demonstrated. Engineered materials, in the fast-emerging research and practice of waterless hydraulic fracturing are also addressed. The challenges of this new research and practice that need integrated solutions are also listed.

The operational challenges presented above are adopted to suggest some future directions of both academic and application-oriented research. The implications of engineering breakthroughs and scientific findings in these new research directions for unconventional reserve extraction include improved energy efficiency and use of environmentally safe materials, which are linked to the science of materials and energy. The exploration of the main aspects of the materials considered in this paper also suggest a direction to tackle research which can reap immediate benefits from academic research efficient systems, combinations and networking. A network that allows all these to connect remains to be developed with continuous dialogue and feedback from research and from industry.

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