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Review

An Overview of Recent Developments and Understandings of Unconventionals in the Vaca Muerta Formation, Argentina

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Abstract: In this article, we comprehensively reviewed Argentina's Vaca Muerta formation, which encompasses a geological overview, advances in extraction technologies, the potential environmental impact, and economic analysis. Detailed geological analysis is discussed, emphasizing the stratigraphy, lithology, and depositional environments of the formation, which is crucial for understanding the distribution and quality of hydrocarbon resources. The latest advancements in hydraulic fracturing and horizontal drilling are explored, which have significantly improved efficiency and increased recoverable resources. The environmental implications of these extraction methods are critically examined. This includes a discussion of the necessity of sustainable practices in hydrocarbon extraction, highlighting the balance between resource development and environmental stewardship. The economic viability of the Vaca Muerta formation is analyzed, with a focus on cost-effectiveness, market trends, and investment patterns. This section assesses the formation's potential as a profitable venture and its impact on the global energy market. Finally, the review anticipates future technological and policy developments. The strategic importance of the Vaca Muerta formation in the global energy sector is underscored, and its potential role in shaping future hydrocarbon exploration and production strategies is examined. In short, this essay not only presents data and findings, but also contextualizes them within the broader scope of energy production, environmental sustainability, and economic viability. This comprehensive approach provides a multi-faceted understanding of the Vaca Muerta formation's significance in the global energy landscape.

Keywords: shale; Vaca Muerta; Argentina; unconventionals; exploration and production

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1. Introduction

In recent years, Vaca Muerta has garnered increasing attention and investment, largely attributed to shifts in government policies that aim to incentivize energy ventures [1]. Predominantly owned by YPF, Argentina's state-owned oil and gas company—holding a 42% stake in the Loma Campana concession which accounts for 47% of all unconventional investments to date—the field has also seen significant involvement from industry heavyweights such as ExxonMobil, Pan American Energy, Petronas, Pluspetrol, Shell, Tecpetrol, and Wintershall [2]. Nevertheless, operational costs remain prohibitive, despite this influx of interest and capital which is mainly due to complex logistical challenges [3].

Originally, the field was exploited using vertical wells; however, by the year 2016, a pivotal shift towards horizontal drilling occurred, as 75% of the wells were either vertical or deviated. This strategic transition was necessitated by the higher productivity rates exhibited by horizontal wells. According to data that was available up to December 2018, the field produced around 80,000 stock tank barrels per day (STB/d), a figure that impressively soared to approximately 291,000 STB/d by February 2023. However, when juxtaposed against similar U.S. unconventional formations, the pace of Vaca Muerta's ramp-up in both production and well-count appears to be more modest [3].

A comprehensive survey of the existing literature reveals a glaring gap: there is an absence of all-encompassing review articles that detail Vaca Muerta's development from multiple perspectives [4–7]. We argue that understanding the intricacies of Vaca Muerta's successful operational history is not just instructive for the field itself but serves as a seminal case study for other unconventional reservoirs also. Harnessing these lessons could facilitate the growth and optimization of similar unconventional formations.

Given this motivating framework, we have elected to craft this review, aiming to be a definitive resource that encompasses all facets of Vaca Muerta's development. This includes a thorough analysis of geological characteristics, the petrophysical properties of the reservoir, drilling methodologies, hydraulic fracturing techniques, post-fracturing management, enhanced oil recovery (EOR) approaches, and phase-specific optimization strategies.

It is important to begin by contextualizing Vaca Muerta within the global energy landscape. As the world grapples with the complexities of transitioning to renewable energy, hydrocarbons remain an indispensable part of the energy mix [8–10]. Within this scope, unconventional reservoirs like Vaca Muerta represent an increasingly important asset, especially given their capacity to produce both gas and liquid hydrocarbons. The Argentinian government, recognizing this potential, has initiated policy shifts to attract both domestic and foreign investments into this promising play.

From a geological standpoint, Vaca Muerta's significance cannot be understated. Comprising a mix of organic-rich shales and interbedded carbonates, its resource-rich strata present both opportunities and challenges [11]. Detailed seismic surveys and core sampling methodologies have been instrumental in mapping the complex geological heterogeneities that characterize the formation [12–14], ultimately guiding drilling and completion activities [15,16].

In terms of petrophysics, the reservoir properties, such as porosity and permeability, are critical determinants of well productivity [17,18]. Advances in downhole logging techniques and lab-based experiments have contributed to a more nuanced understanding of these petrophysical attributes. Such insights have been pivotal in optimizing drilling practices [19–22], which have evolved from traditional vertical wells to more complex deviated and horizontal trajectories [23,24]. High-resolution reservoir simulations and geomechanical models are frequently employed to predict the impacts of different drilling and completion scenarios [25].

Hydraulic fracturing has been another cornerstone of Vaca Muerta's development. The nuances of fracturing fluid compositions, proppant types, and injection protocols are tailored based on reservoir conditions [26,27]. Extensive research has been conducted to assess the effectiveness of various fracturing techniques, including sliding sleeve and plug-and-perf approaches [28,29]. Post-fracturing operations focus on wellbore clean-up, flowback management [30–32], and reservoir pressure maintenance, often leveraging enhanced oil recovery (EOR) techniques, like CO_2 or gas injection, to improve ultimate recovery [33–36].

One of the ongoing challenges has been operational optimization [37]. This involves an iterative process of data collection, analysis, and strategy refinement across all phases of reservoir development [38]. Emerging technologies like machine learning and data analytics are increasingly being employed to analyze real-time production data [39–41], thereby identifying bottlenecks and suggesting optimization strategies.

The financial aspects of developing Vaca Muerta also warrant discussion. Although investment has been steadily flowing into the field, high operational costs driven by logistical constraints, such as transport and infrastructure, remain a significant hindrance. Despite these challenges, the field's enormous resource potential continues to attract investment and research, thus promising a robust future.

In conclusion, this review article aims to serve as a comprehensive guide to Vaca Muerta's development, dissecting its various aspects with the intent of providing valuable lessons for the advancement of similar unconventional reservoirs. Through meticulous research and a multi-faceted approach, we aspire to fill the existing gap in the literature and contribute meaningfully to the body of knowledge surrounding Vaca Muerta and unconventional reservoirs at large.

2. Geological Context and Current Production Base Status

The Neuquén Basin, hosting the Vaca Muerta formation, stands as a central figure in Argentina's energy sector, contributing significantly to the national output of oil and gas. The Vaca Muerta formation, nestled within this basin, showcases a remarkable geological and stratigraphic complexity with significant implications for hydrocarbon exploration and production.

The formation's thickness demonstrates considerable variation, ranging from 60 m at the basin's edges, to 520 m towards the center; this is indicative of the dynamic depositional environments and tectonic activities that have shaped the basin over millions of years. This variation in thickness is paralleled by a broad range of matrix permeabilities and porosities, which fluctuate between 4% and 14%, with an average of about 9%. Such diversity in physical properties underscores the heterogeneity of the Vaca Muerta formation, affecting both the exploration strategies and the production potential.

The total organic carbon (TOC) content and thermal maturity (Ro) across the formation are notably variable, further emphasizing the formation's complex geology (Figure 1). These variations contribute to the differing hydrocarbon qualities within the formation, ranging from heavier black oil in the southeast to lighter dry gas towards the northwest. The overpressured nature of the formation, with pressure gradients between 0.6 and 0.9 psi/ft, enhances its attractiveness for hydrocarbon extraction via potentially improving flow rates and recovery efficiencies.

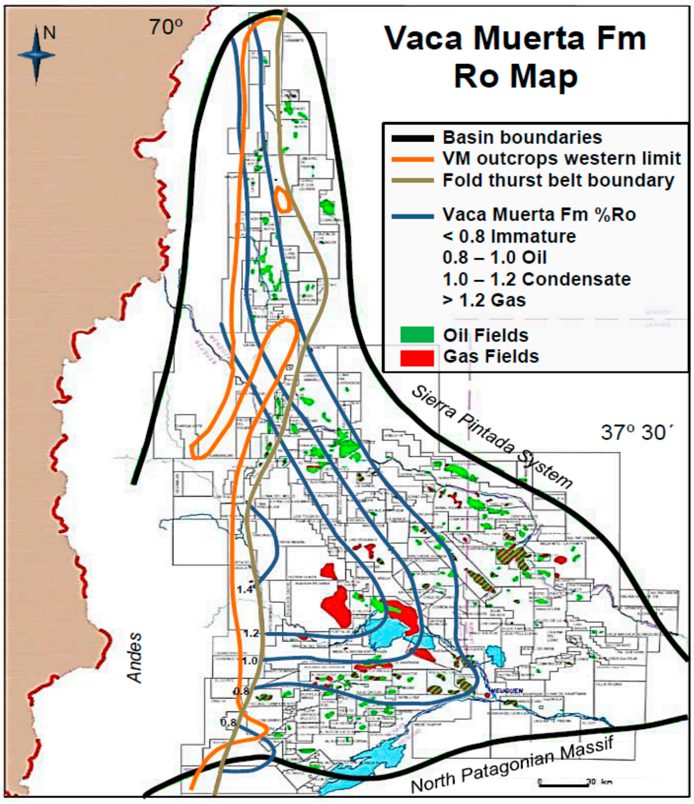

Figure 1. Ro distributions in the Vaca Muerta formation producing oil and gas. Reprinted with permission from Ref. [42]. Copyright 2018, Society of Petroleum Engineers.

Adding to the geological and operational perspective, the lithology of the Vaca Muerta formation comprises a mix of shale, marls, carbonates, and sandstones. Ternary mineralogical diagrams highlight a relatively low clay content with a dominance of quartz and carbonates, pointing to a substantial heterogeneity in mineral distribution (Figure 2). This heterogeneity is closely tied to the paleogeographic conditions and diagenetic evolution of the formation. Vertically, there is a trend of decreasing quartz and clay content from top to bottom, while the TOC content shows an upward trend, ranging approximately from 2% to 15%. This variability in mineral and organic content has direct implications for the formation's hydrocarbon production potential.

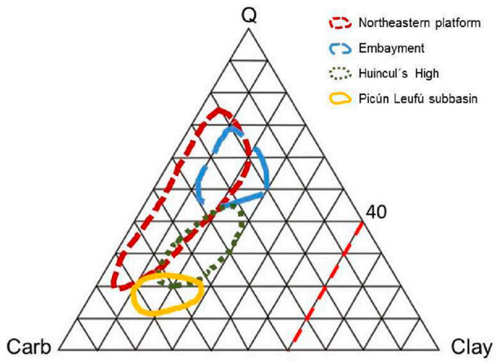

Figure 2. Ternary mineralogical diagram across various sub-basins of the Vaca Muerta formation. Reprinted with permission from Ref. [42]. Copyright 2018, Society of Petroleum Engineers.

Recent operational data, such as the Vista Oil & Gas Q2 2020 earnings webcast, shed light on the production capabilities of the Vaca Muerta formation. The analysis of production data from ten wells, particularly two high-performing wells in the La Cocina area of Pad 3, reveals peak production rates of up to 2000 barrels per day (equivalent to 300 metric tons per day), attributed to their positioning within a shale layer that is rich in TOC. Conversely, wells in other areas, like Pads 1 and 2, despite periods of shut-in, also demonstrate substantial production rates, further evidencing the formation's significant role in Argentina's hydrocarbon sector.

3. Drilling

3.1. Gas Kick

Intricacies such as elevated pore pressure and unyielding lithology appear to be endemic features of the Vaca Muerta formation, as evidenced by the drilling outcomes across multiple boreholes in the area. The Parva Negra Oeste site, which aims to exploit this formation, has been particularly problematic, manifesting a 40% well abandonment rate, due to operational complexities. In the surrounding area, wells have encountered issues ranging from gas influxes to fluid losses at disparate stratigraphic levels. During the drilling process, two primary geological obstacles emerged: the actual lithological hardness surpassed projections by more than half, and the pore pressure at shallower strata exceeded initial estimates by 5–20% [43].

To optimize well design, data from adjacent boreholes within a 15 km radius were scrutinized. This analysis informed decisions on setting casing depth, defining the operational mud weight window, and planning for emergency casing scenarios, all while prioritizing wellbore stability and risk mitigation. Managed pressure drilling (MPD) techniques were implemented to counteract the gas influxes encountered at multiple stratigraphic intervals [44]. The unexpected lithological hardness necessitated a reassessment of the formation's mineralogical composition. The presence of carbonate cement in various strata was found to contribute to the increased lithological hardness, prompting modifications to drilling parameters. MPD strategies were also effective in mitigating the elevated pore pressures, although some wells still experienced isolated gas influx events.

3.2. Extended Drilling

While most drilling operations in the region typically employ horizontal wells with lateral extensions ranging from 2500 to 2800 m, the Loma Campana Project took an unconventional approach. The project aimed to exploit more challenging reservoir zones by designing wells with lateral stretches exceeding 4000 m. A comprehensive feasibility study was conducted by Calegari et al. from YPF and Chevron, which included generating prospective well designs, outlining specialized procedures, and identifying the requisite engineering solutions and toolsets.

Initial test wells were drilled and swiftly fine-tuned to facilitate broader development using the innovative well architecture. A host of challenges emerged during the drilling process, particularly concerning wellbore tortuosity, most notably between the measured depths of 18,000 feet and the total depth (TD). Elevated tortuosity led to complications such as ineffective hole cleaning, weight distribution issues, augmented torque requirements, and increased energy consumption by the drilling rig. These challenges were particularly pronounced in the first two wells of Pad A, where torque demands nearly exceeded the capacity of the Top Drive system, necessitating the maximum power output from the rig's generators.

During the lateral drilling phases, time-dependent instabilities were noted, particularly around the landing zones. These instabilities led to pipe-sticking tendencies. The prolonged exposure of the lateral section (exceeding 48 h) due to slow tripping operations resulted in alterations to fluid properties and rheology, triggering the emergence of cavings and gas influxes that required management. To address these issues, the team deployed a specialized mining rig in order to install deeper conductor casings at depths between 40 and 50 feet, a significant departure from the previous 9–12 foot depths in Pad A. Fluid specifications were also re-evaluated, leading to the introduction of potassium sulfate as a clay stabilizer to enhance wellbore integrity [45,46].

The extended drilling strategy employed in the Vaca Muerta formation underscored the necessity for tailored approaches that manage unique challenges, like tortuosity and geomechanical instabilities. Insights gleaned from the wells that were drilled to the total depth were cataloged for future reference. Key action items for subsequent projects included the adoption of casing-while-drilling (CWD) techniques [47,48], the selection of rigs with an adequate operational capacity, improved tortuosity control measures, and optimized bottomhole-assembly (BHA) configurations for the production intervals.

3.3. Azimuthal Hold Technology

In the Vaca Muerta formation, directional control during drilling was compromised due to limitations in the existing azimuthal hold technology. To address this, a firmware upgrade was introduced to refine the estimation of the near-bit rotational azimuth, thereby enhancing the precision of the steering head.

Field tests across the various stratigraphic layers of Vaca Muerta were executed in order to assess the impact of the updated azimuthal hold technology on the drilling performance. The firmware advancements, coupled with modifications in the drilling system architecture, led to a marked decrease in wellbore tortuosity and a surge in the rate of penetration (ROP) by over 32% for the lateral sections in the Loma Campana field.

These improvements translated into significant operational efficiencies, including a reduction of more than 40 h in the drilling cycle time for the production zones. The diminished tortuosity also expedited the tripping and casing installation processes by 6–10 h. Enhanced trajectory control not only minimized wellbore tortuosity, but also reduced uncertainties in wellbore placement, thereby optimizing reservoir navigation. This had the added advantage of facilitating subsequent completion operations by lowering wellbore friction, which impacts wireline and coiled tubing activities.

Situated in the southeastern quadrant of Argentina's Neuquén Basin, the Loma Campana field has been the site of over 150 horizontal wells since 2015. The implementation of the new azimuthal hold firmware, along with the alterations to the bit's cutting structure, resulted in a 32% reduction in absolute tortuosity when benchmarked against wells that were drilled in the same stratigraphic layer (as indicated in Figure 3). This enhanced trajectory control also led to a friction factor reduction of up to 45%, significantly boosting the operational performance and reducing the time required for tripping and casing installations [49].

Well Name / Formation	Drill Bit	Abs Tort	OHFF
Well #1 - Formation O	Original	1.78	0.33
Well #2 - Formation C	Original	1.93	0.33
Well #3 - Formation C	Original	2.14	0.34
Well #4 - Formation P3	Modified	1.25	0.25
Well #5 - Formation P4	Modified	1.2	0.25
Well #6 - Formation O	Modified	1.2	0.18

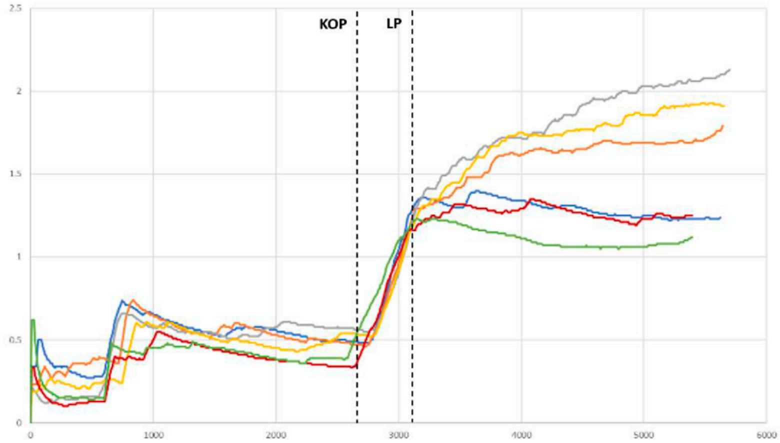

Figure 3. Comparative analysis of absolute tortuosity and OHFF in wells utilizing azimuthal hold firmware: original vs. modified bit cutting structure. Reprinted with permission from Ref. [49]. Copyright 2018, Society of Petroleum Engineers.

4. Hydraulic Fracturing

4.1. Child and Parent Well Effect

To circumvent the detrimental interplay between parent and child wells, one of the key mitigation strategies involved pressurizing the parent well with water [50,51]. The objective was to sustain the productivity of the parent well, even as new adjacent child wells were drilled and fractured. The completion architecture of one such child well was specifically tailored to address the challenges arising from its close proximity to the parent well. To quantify the extent of production interference along the fracture networks of these horizontal wells, a combination of water–oil tracers was utilized.

The techniques deployed effectively preserved the output levels of the parent well, while substantially mitigating the decline in the estimated ultimate recovery (EUR) in the child wells [52]. On average, child wells exhibited a productivity reduction of approximately 35% per stimulated foot when compared to the parent well. However, this decline was less severe in child wells situated at greater distances from the parent well.

A comparative analysis was conducted between the Vaca Muerta formation and analogous fields where these mitigation strategies were not applied. The findings revealed that the approaches tested in the Vaca Muerta formation were successful in bolstering the asset value by averting EUR degradation. When considering the potential hydrocarbon volumes recoverable in a factory-style development setting, the impact of implementing these techniques could be considerable, particularly when multiple horizontal wells are in play (Figure 4).

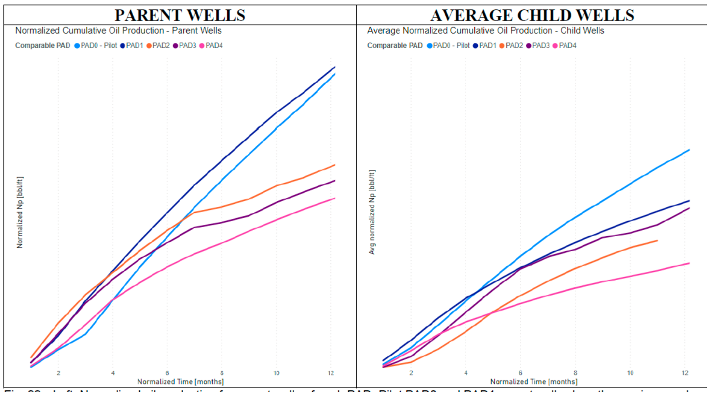

Figure 4. Annual normalized oil production for parent wells across all pads: peak performance in pilot pads PAD0 and PAD1 (**left**). Average normalized oil output for child wells in each pad, with uniform Y-axis units for parent–child comparison (**right**). Notably, PAD0 child wells excel, whereas PAD1 child wells show a marked decline when compared to the PAD1 parent well. Reprinted with permission from Ref. [52]. Copyright 2018, Society of Petroleum Engineers.

4.2. Diagnostic Fracture Injection Test (DFIT) New Approach

DFIT is a standard tool for reservoir analysis [53–56], but conventional approaches often fall short in accurately determining reservoir attributes. A novel type-curves approach has been developed to increase the reliability of DFIT outcomes, thereby improving the Vaca Muerta reservoir characterization.

The formation presents specific challenges, such as wax accumulation in gas-lift-injected wells [57,58], necessitating the use of specialized chemicals and treatments. Conventional techniques for generating performance curves have proven inadequate for Vaca Muerta's unconventional wells, leading some to question the applicability of traditional DFIT methods in horizontal drilling scenarios.

The shift toward developing low-permeability reservoirs has necessitated a reevaluation of well-testing methodologies for parameter extraction. González et al. addressed these issues with their type-curves approach, which does not rely on specific flow regimes for parameter estimation. They demonstrated how this method enhances Vaca Muerta characterization through more accurately mapping pore pressure and delineating permeability ranges. Case studies were presented to validate the efficacy of this approach in comparison to the traditional methods [59].

4.3. Stimulated Reservoir Volume (SRV) Characterization

The initial characterization of SRV is crucial for optimizing well performance and development plans [60,61]. Cugnart et al. developed a methodology for assessing SRV in Vaca Muerta wells, focusing on the analysis of flowback data to gauge critical hydraulic fracture and reservoir attributes like fracture half-length and conductivity [62].

The utility of flowback data is underscored for various applications [63,64], such as refining completion methods, optimizing flowback sequences, adjusting choke strategies, characterizing SRV, and projecting production. The team applied this methodology across a range of Vaca Muerta wells, each with distinct fluid characteristics, landing zones, and fracturing designs. They employed a specialized Excel-based application, known as the 'Flowback Analysis Tool' (FLOAT), for their evaluations.

In their theoretical framework, hydraulic fractures were modeled as fluid reservoirs with diverse shapes and geometries. The study delineated three primary flow regimes: initial radial water flow within the fracture, subsequent fracture depletion, and a final stage involving linear formation flow coupled with multi-phase fracture depletion. As a case study, the team analyzed well VM03 in Vaca Muerta, which offered one of the most robust datasets. The analysis, based on approximately 5.6 days of high-resolution flowback data, was successfully conducted despite various challenges.

4.4. Fracturing Fluids

In the initial stages of hydraulic fracturing within the Vaca Muerta formation, traditional fluid systems such as linear and crosslinked guar-based polymers were commonly employed [65]. However, the industry has recently shifted towards the use of Polyacrylamide-based viscosifying friction reducers (VFR) in specific regions of the Neuquén Basin, including the Aguada Pichana Oeste and Lindero Atravesado blocks [66].

VFRs present notable economic advantages, including an average cost reduction of 34%. They also necessitate fewer chemical additives and on-site equipment. Furthermore, these fluid systems are characterized by reduced pumping pressures and simplified pumping schedules. Pilot tests in the Neuquén Basin have demonstrated promising early production metrics, outperforming older fluid systems. To further optimize operations, it is recommended to employ larger storage containers, such as ISO tanks, and to utilize dry friction reducer powder in order to minimize expenses.

4.5. Well Completion

Bonapace et al. explored methods to enhance hydraulic fracturing in the Vaca Muerta shale, emphasizing the critical role of rock characteristics and stress factors. They employed a 'hybrid' fracturing approach that merges the benefits of both 'plug and perf' and 'ball and sleeve' techniques [67].

Crespo et al. focused on technological advancements in well completion, utilizing machine learning to forecast well performance based on past data and geological attributes. Their findings indicate that machine learning offers a reliable method for predicting well performance and selecting the most effective fracturing fluids, especially in geologically complex areas such as Vaca Muerta [68].

Lerza et al. assessed well performance in Vaca Muerta using contemporary rate transient analysis (RTA). They examined 168 wells and sorted them into three design categories (A, B, C) based on variables such as proppant intensity and fluid per cluster. Design Group A featured moderate proppant intensity with a broad range of fluid per cluster values (Figure 5). Design Group B had reduced proppant intensity and lower fluid-per-cluster values, while Design Group C significantly increased proppant intensity but reduced fluid-per-cluster values. Their analysis led to statistically sound recommendations concerning the economic benefits of various completion designs [69].

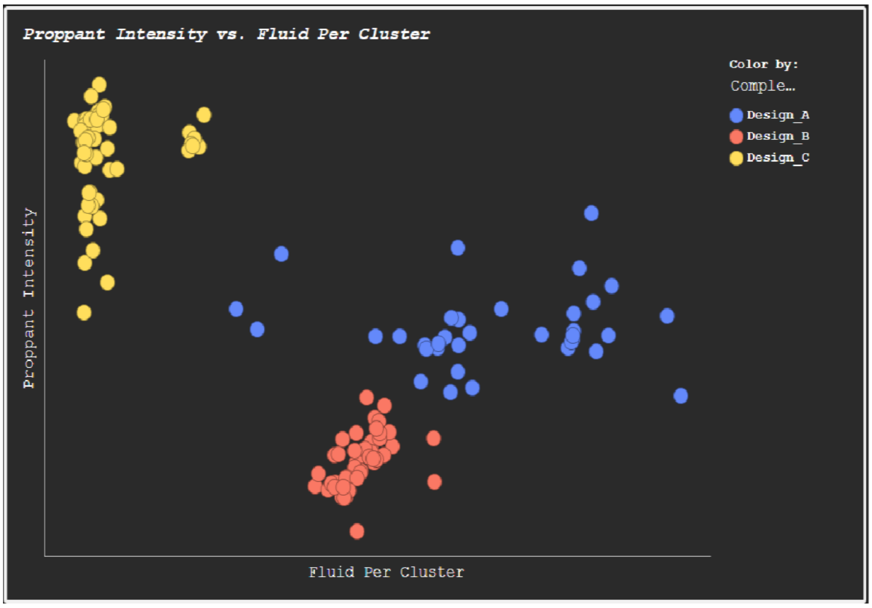

Figure 5. Classification of completion designs based on the fluid per cluster and proppant intensity. reprinted with permission from Ref. [69]. Copyright 2018, Society of Petroleum Engineers.

The approach to well completion in Vaca Muerta is continually evolving, with an emphasis on tailoring hydraulic fracturing methods to the formation's intricate geology. Technological advancements like machine learning and updated RTA techniques are pivotal in this optimization effort. These methods not only enhance the economic feasibility of well completions, but also promote more sustainable and efficient resource extraction.

5. Geomechanics

5.1. Geostress Status

In the Vaca Muerta formation, a dynamic test known as the pump-in flowback sequence has been employed to gauge closure stress (Figure 6). This test involves a series of steps that include injecting fluid into the formation (Figure 6), allowing it to flow back through a predetermined choke, monitoring pressure rebounds, and reinitiating fracture openings. The exact timing of fracture closure during the flowback phase is ascertained through a volume–pressure graph. The intersection point of the extrapolated pre-closure and post-closure flowback curves on this graph pinpoints the exact moment of fracture closure [59,70].

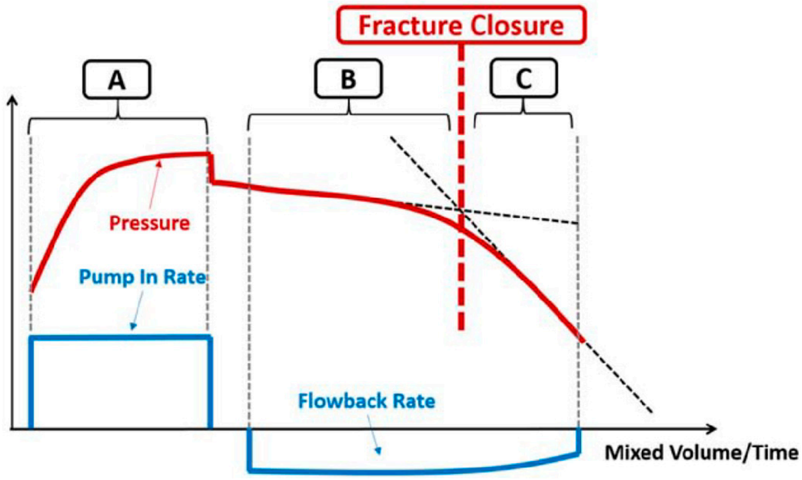

Figure 6. Methodology for pump-in measurement of closure stress. Reprinted with permission from Ref. [70]. Copyright 2018, Society of Petroleum Engineers.

In the Vaca Muerta formation, variations in closure stress are notably depth dependent. The deeper zones, often referred to as "La Cocina," show lower closure pressures, likely due to their increased organic matter, which mitigates the impact of tectonic stresses. Conversely, the shallower regions of the Vaca Muerta formation exhibit higher net pressures, indicating a need for potential adjustments in completion approaches or improved fracture containment strategies [70]. Areas within the formation that have low organic content but are rich in carbonate layers display the highest closure pressures. The complexity of these stress distributions is exacerbated by the tectonic activity of the adjacent Andes Mountains, underlining the necessity for a nuanced understanding of these factors for effective hydraulic fracturing (Figure 7).

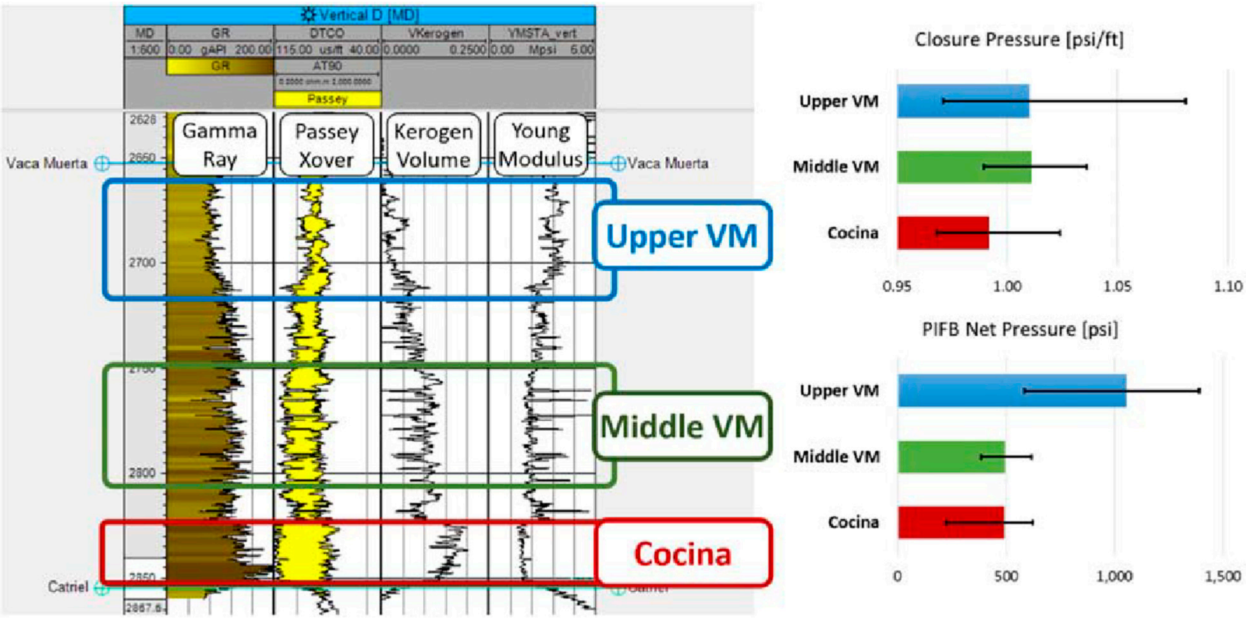

Figure 7. Logging data and variations in closure pressure/net pressure at various depths in Vaca Muerta, covering upper, middle, and Cocina sections. Reprinted with permission from Ref. [70]. Copyright 2018, Society of Petroleum Engineers.

5.2. Static and Dynamic Geomechanics

Due to the impact of varying facies on geomechanical properties, the Vaca Muerta formation exhibits a wide range of values for both Young's modulus and Poisson's ratio. As illustrated in the following figure, Young's modulus varies from 1 to 8 GPa, while Poisson's ratio ranges from 0.18 to 0.38. This demonstrates significant heterogeneity within the formation (Figure 8).

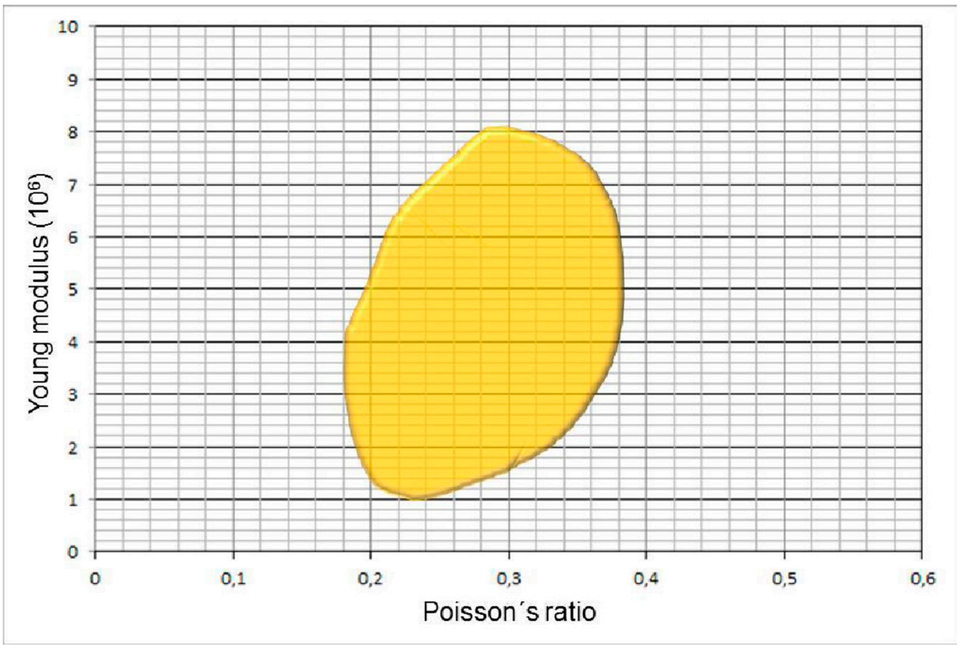

Figure 8. Distribution of Young's modulus and Poisson's ratio in the Vaca Muerta formation. Reprinted with permission from Ref. [42]. Copyright 2014, Society of Petroleum Engineers.

In a dynamically active tectonic environment, precise stress characterization is essential for optimizing hydraulic fracturing operations. Elevated treatment pressures in hydraulic fracturing can induce additional rock rigidity and broaden the influence of stress shadows, thus necessitating meticulous stress state assessments for successful fracturing.

Espinoza et al. collected core samples from two boreholes in the Neuquén Basin, specifically targeting the Vaca Muerta formation, in order to conduct both static and dynamic rigidity evaluations. For static rigidity assessments, the rock specimens are subjected to creep conditions for an adequate duration to mitigate their influence on the resulting elastic metrics. These measurements are taken during both the loading and unloading stress phases at roughly a third of the peak deviatoric stress level. Traditional analyses employ a triaxial approach, utilizing horizontal, vertical, and 45-degree oriented samples from the same depth to compute all rigidity coefficients. Dynamic rigidity, on the other hand, is ascertained from P- and S-wave velocities in both the horizontal and vertical specimens and is also less susceptible to variations in confining pressures. In terms of dynamic rigidity, mudstones exhibit clear anisotropy, while andesites are nearly isotropic and display 30 to 60% greater rigidity than any mudstone.

The examined rock categories include mudstone, calcareous mudstone—which has fluctuating carbonate levels and constitutes the bulk of the stratigraphic sequence—and andesite, a silica-rich igneous rock. The findings indicate that mudstones display anisotropy in both static and dynamic conditions, whereas andesites exhibit limited anisotropy but possess high rigidity. The static Young's modulus demonstrates considerable sensitivity to stress changes, with peak variations of +32% for mudstone, +38% for calcareous mudstone, and 31% for andesite as the confining pressure increases (Figure 9).

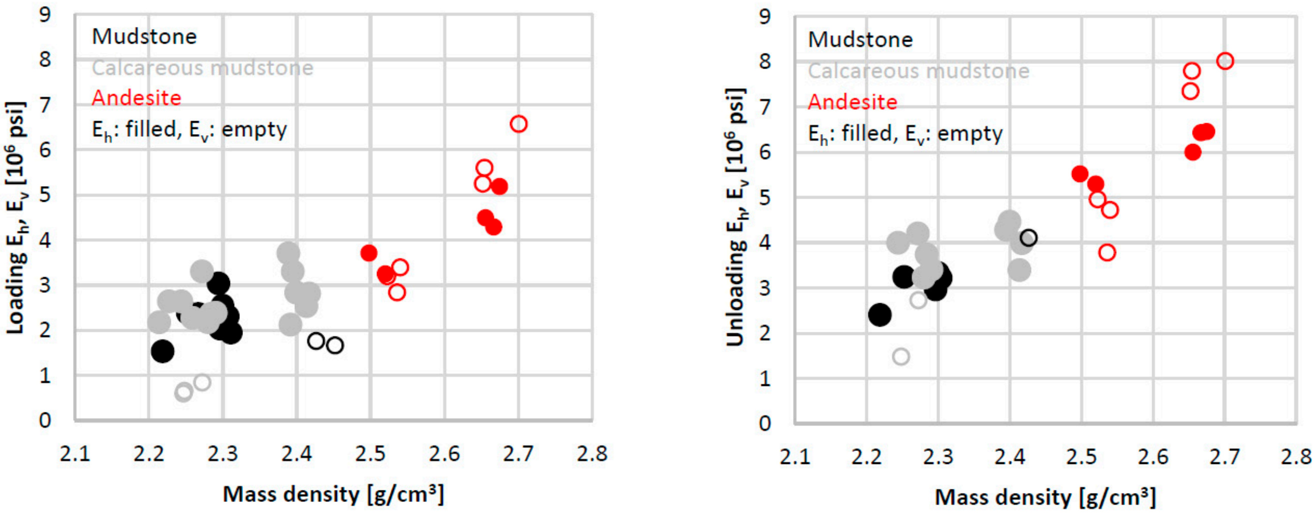

Figure 9. Young's modulus during loading and unloading vs. mass density in horizontally and vertically oriented samples. Reprinted with permission from Ref. [71]. Copyright 2014, Society of Petroleum Engineers.

The results of the dynamic testing indicate a strong correlation between stiffness and density, with andesite exhibiting greater values than calcareous mudstone, which in turn is greater than mudstone. In the same set of tests, differences between loading and unloading were observed. The Young's modulus values obtained during loading were found to be 50–75% of those obtained in dynamic conditions. The unloading values should be used for predicting the stress shadow during hydraulic fracturing, given the rapid nature of this process. Additionally, the ratio between unloading and loading is an important parameter for quantifying plastic deformation. Static results show that, for all samples, the ratio of Young's modulus during horizontal unloading to loading is approximately 1.4. For vertical samples, the values for the two types of mudstone and andesite are 2 and 1.3, respectively (Figure 10).

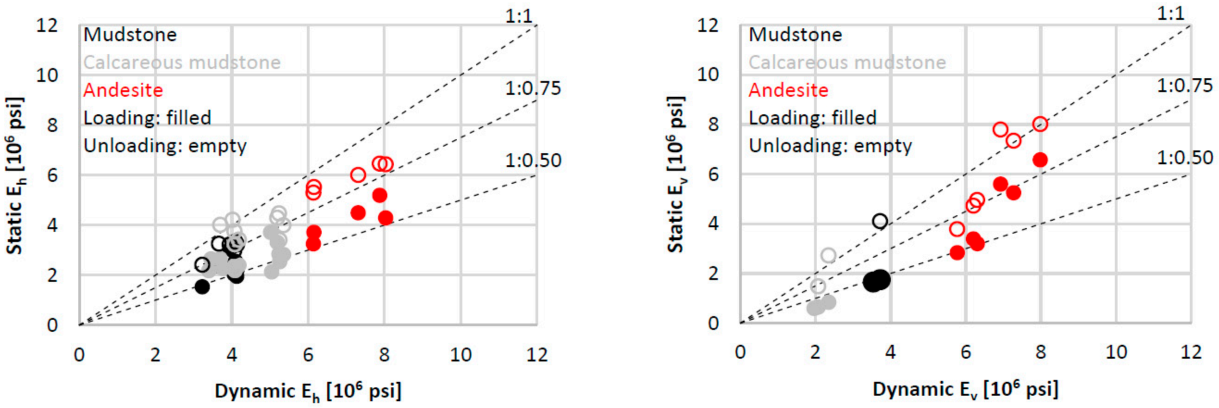

Figure 10. Static and dynamic Young's modulus for different lithologies. Reprinted with permission from Ref. [71]. Copyright 2014, Society of Petroleum Engineers.

6. Enhanced Oil Recovery

In the Vaca Muerta shale formation, the prospects for enhanced oil recovery (EOR) are notably promising. This is attributed to the abundant in situ hydrocarbon reserves, subpar yields from initial extraction methods, and a well-established infrastructure and data landscape. A thorough assessment has been conducted to gauge the efficacy of multiple EOR technologies in elevating both initial and ultimate oil recovery rates for horizontal wells in this specific shale play.

Chemical additives designed for enhanced recovery can be integrated into the initial hydraulic fracturing stage. This early intervention contrasts with the more conventional EOR techniques, which are generally deployed later in the well's operational lifecycle. The advantage of this early stage chemical introduction is twofold: it not only augments immediate production, but also shortens the time needed to replenish fluids in a depleted reservoir, thereby improving the overall economic viability of the well. While the existing literature does not provide explicit details on the chemical compositions used, reservoir simulation models do emphasize the potential gains achievable through such treatments.

6.1. Solvent Injection

Initial field activities focused on the use of cyclical water injection as a strategy for hydrocarbon recovery. However, this method proved ineffective, largely due to the phenomenon of capillary pressure hysteresis. This setback prompted a detailed examination of the microstructural properties of the Vaca Muerta shale. The formation is characterized by substantial microstructural heterogeneity, often varying within minute spatial scales. This fluctuation is ascribed to the protracted sedimentation periods that are typical of shale reservoirs, in contrast to their conventional counterparts.

Traditionally, the Vaca Muerta formation has been classified as predominantly water-wet—a conclusion drawn from the minimal recovery of fracturing water during production phases. However, recent studies have identified regions with both water-wet and oil-wet characteristics. Zones with oil-wet attributes demonstrated elevated porosity levels, potentially signaling greater permeability when compared to water-wet areas. Laboratory analyses indicate that targeted interventions could amplify the initial oil production rates by as much as 20%. The organic porosity in the Vaca Muerta shale, serving as the ingress point for chemical agents, could further augment both permeability and initial production rates.

The introduction of dimethyl-ether into the Vaca Muerta formation presented unique challenges, necessitating a nuanced understanding of the rock's microstructure to optimize the effectiveness of enhanced oil recovery (EOR) methods. The objective was to formulate an EOR cocktail that would favorably modify interfacial tension, viscosity, and wettability. The injection of a viscosity-reducing solvent also had the potential to alter the wettability of the formation, thereby improving matrix connectivity and initial oil production rates.

A series of laboratory tests were conducted to characterize different oil and stimulation fluid systems, with the stimulation fluid serving as the solvent carrier for dimethyl-ether. The experimental suite included porosimetry, pycnometry, surface area assessments, partition coefficient evaluations, and viscosity alteration/swelling tests. These experiments underscore the promising potential of EOR techniques in the Vaca Muerta formation, emphasizing the critical role of understanding rock microstructures and the influence of chemical agents in optimizing oil recovery.

6.2. Countercurrent Imbibition

Tuero et al. suggested a countercurrent water imbibition strategy aimed at enhancing oil recovery [72]. This approach involves a cyclical regimen of water injection, soak periods, and production phases, which can be reiterated until the influence of capillary forces wanes. The theoretical framework for this method hinges on the pronounced capillary effects observed in shale formations, which are further substantiated by attributes like low permeability, dual-phase wettability, and the coexistence of overpressure conditions with low water saturation levels.

Laboratory tests were performed on core specimens sourced from diverse stratigraphic layers within the Vaca Muerta formation. Subjected to reservoir-temperature water, these cores exhibited a strong affinity for water-wet conditions. During the imbibition experiments, the cores regained between 40% and 60% of their original oil in place (OOIP).

Field trials were also executed, involving the injection of over 9400 barrels of water into a tri-stage vertical well. Oil samples were collected from the wellhead after a 12-day interval. Downhole sensors revealed a consistent oil flow through the perforations, leading to a lighter fluid column during the shut-in phase. Numerical simulations, utilizing actual field data from the Vaca Muerta formation, were employed to assess potential outcomes and uncertainty impacts. The optimized EOR scenario demonstrated an incremental resource gain of roughly 40% when compared to a baseline case devoid of EOR interventions (as illustrated in Figure 11).

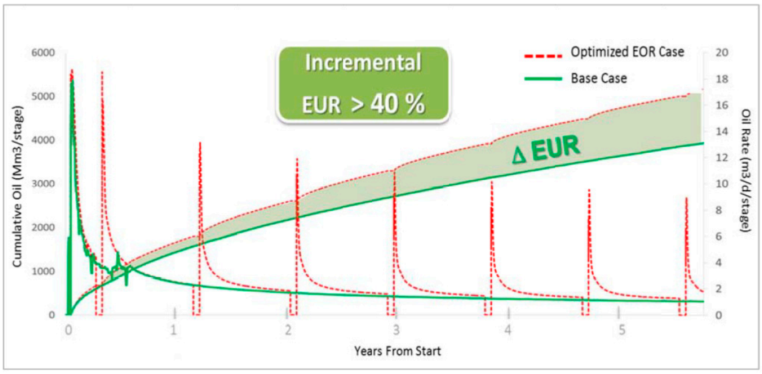

Figure 11. Comparative analysis of base and optimized scenarios using the recommended EOR methodology. Reprinted with permission from Ref. [72]. Copyright 2014, Society of Petroleum Engineers.

Should this EOR technique prove effective, it holds the potential to significantly influence both the valuation and economic feasibility of similar projects. Not only could it enhance oil recovery at a relatively low operational cost, thereby converting resources into proven reserves, but it could also mitigate operational hurdles such as paraffin build-up, pressure sustainability, and the need for extensive acid treatments.

7. Production

7.1. Gas Lift

Artificial lift systems, especially gas lifts, are commonly employed in the Vaca Muerta formation, but they come with their own set of challenges, such as the accumulation of wax, necessitating chemical interventions. Masud et al. conducted a study focusing on the Bajada del Palo Oeste field within the Vaca Muerta formation, which has 55 operational wells, 40 of which utilize gas lift systems. They examined the complexities of using gas lift in shale formations like Vaca Muerta, where production rates are highly variable [73].

Their research emphasized the problem of wax build-up in wells when using a gas lift. The first significant instance of this issue appeared 42 months after successful well tie-in and 23 months post gas injection initiation. A range of chemical solutions and alternative methods were employed to manage and reduce wax accumulation.

The team also explored the optimization of gas injection strategies. Conventional techniques for generating performance curves proved inadequate for the unconventional wells in this formation. They proposed an AI-driven model, designed to optimize gas injection at the PAD level, rather than solely focusing on individual wells.

Additionally, the study delved into slickline management and troubleshooting procedures. Real-time monitoring and remote operations were implemented to reduce operational downtime. Key metrics like gas injection rates, casing pressures, and wellhead pressures were continuously monitored to swiftly identify and address system failures.

7.2. Production Rate Calculation

Reliable production rate estimations are essential for well-performance optimization. Cano and colleagues introduced a novel workflow that integrates a multiphase choke correlation with an equation of state (EOS) to enhance the accuracy of these calculations. The field under study comprises 30 horizontal wells, organized into three-well pads and drilled at varying depths. Initial well testing is conducted to assess productivity and to prevent contaminants like sand and liquids from entering plant facilities [74].

Choke management is vital for mitigating operational issues such as sand production. Initial choke settings are configured with a 12–14/64″ diameter to facilitate continuous water flow and prevent hydrate accumulation. Adjustments to choke size are incrementally made in order to manage sand output. During the initial 3–4 month clean-up phase, the choke management plan is frequently revised to address challenges like hydrate and sand accumulation, liquid overproduction, and mechanical issues like valve failures. A cross-disciplinary approach involving various engineering teams was deemed essential for overcoming these challenges [74].

Advanced AI algorithms for gas injection optimization and new workflows for production rate calculations are anticipated to be increasingly important in future operations. Aragon et al. developed a methodology specifically for the Vaca Muerta formation, which is particularly useful when a separator is unavailable for production testing. Their approach employs a choke correlation for mass calculation and an EOS for determining water cut and gas to oil ratio (GOR), aiming to bolster the confidence in production rate estimates. The study also emphasizes the role of wellhead chokes in flow regulation and backpressure maintenance.

Furthermore, the authors explore the thermodynamic properties of fluids in the Vaca Muerta formation, noting the presence of a wide range of hydrocarbon types. In scenarios where pressure-volume-temperature (PVT) analysis is unavailable, baseline PVT data from analogous regions can be employed. The authors validate their methodology by comparing calculated and actual separator test results across multiple wells, claiming a significant reduction in error rates, with discrepancies ranging between 2–5%, based on historical data.

8. Integrated Development in Vaca Muerta

Rodríguez et al. utilized a range of analytical methods, including X-ray diffraction, scanning electron microscopy, and mechanical testing, to examine the formation's characteristics. Their study delved into the mineralogical makeup, mechanical attributes, and stress-response behavior of shale samples. They determined that the Vaca Muerta shale is mineralogically intricate and displays anisotropic mechanical properties; these are factors that should be integrated into hydraulic fracturing plans [75].

Buijs et al. enhanced the comprehension of fractured well performance in Vaca Muerta through an engineering-centric methodology. They outlined a comprehensive strategy for model characterization, constraint, and validation, incorporating pre-fracture diagnostic injections, core sample data, and post-fracture production metrics. Their work emphasized the role of diagnostic fracture injection tests (DFITs) in data collection, concluding that an in-depth grasp of pore pressure, permeability, and stress conditions is vital for hydraulic fracturing optimization in this formation [76].

Pilot tests and modeling initiatives have underscored the complex mineralogical structure and anisotropic mechanical behavior of the Vaca Muerta shale. They also highlighted the significance of wellbore stability, fracturing fluid chemistry, and the necessity for data-centric methodologies in hydraulic fracturing design. These findings are indispensable for scientists, engineers, and decision makers who are engaged in the exploitation of the Vaca Muerta shale, one of South America's most promising unconventional hydrocarbon reserves.

9. Optimization

Maximizing the potential of Vaca Muerta requires a comprehensive strategy that combines geological insights, cutting-edge drilling and completion methods, and nuanced reservoir management practices. The synergy of these components is essential for both the financial and functional optimization of this non-traditional resource.

9.1. Geological Characterization and Sweet Spots

A case by Shell Argentina is used to showcase the optimized selection of sweet spots. The company has been engaged in the Vaca Muerta formation since 2012, with a focus on optimizing dual-layer development, particularly in the complex upper Vaca Muerta strata. The company has honed its stratigraphic understanding of this upper layer, linking it to factors such as drilling sweet spots, reservoir containment, and pay thickness. A technologically advanced multi-well pad is in the planning stages, featuring fiber optics, chemical markers, microseismic monitoring, and the geochemical analysis of extracted oils. Two primary drilling targets have been identified in both the lower and upper Vaca Muerta layers. While the lower layer is relatively straightforward, the upper layer presents complexities due to its unique depositional environment.

Microseismic observations revealed event concentrations that varied by direction between the upper and lower layers, suggesting the presence of a fracking barrier. Geochemical analysis further confirmed that oil production was exclusive to each layer. Sweet spots were identified using a seismic-based static reservoir model. One of the primary challenges in the co-development of these layers is the risk of vertical interference, which is currently under evaluation. A robust data collection strategy is set to be implemented, encompassing fiber-optic monitoring, microseismic data, geochemical markers, chemical tracers, and interference tests.

9.2. Reservoir Management and Production Optimization

The case by Altman et al. is used to showcase production optimization in Vaca Muerta. They employed a multidisciplinary approach to enhance oil production through reservoir simulation. The team initially examined the disparate production rates among three vertical wells in Vaca Muerta's shale deposits. An integrated methodology, incorporating history matching in reservoir simulation, was then applied to pinpoint the factors contributing to these production variances. Production determinants were classified into three categories: reservoir quality (RQ), completion quality (CQ), and additional variables influenced by human intervention, such as pore pressure, matrix permeability, and total organic carbon, among others.

The study concluded that relying solely on production data is inadequate for comprehending the variances between different exploration zones, given the multiple factors like geological and fluid inconsistencies and completion methods. The research focused on a 570-square-kilometer region, ranging from volatile oil zones in the west to more stable black oil regions in the east. Despite Well 3 having the least favorable hydrocarbon-filled porosity, it exhibited superior production rates.

The findings underscore the unique challenges in Vaca Muerta, including intricate stress patterns, thermal maturity variations, and formation water production. The study also emphasized the difficulty in determining the mobility of hydrocarbon-filled porosity, particularly in zones rich in liquid hydrocarbons.

9.3. Real-Time Optimization

Quishpe et al. employed real-time data analytics and artificial intelligence to optimize shale oil wells in Vaca Muerta's Loma Campana field [77]. The study focused on 130 active wells with the objective of minimizing production losses by detecting issues such as choke erosion and paraffin blockages in a timely manner. The field, which has over 540 drilled wells and 15 production facilities, employs a range of extraction methods and is remotely supervised. The study underscored the challenges of monitoring wells that primarily rely on wellhead pressure data, and also critiqued the limitations of existing alarm systems based on pressure thresholds.

Predictive modeling was conducted using the Prophet package, which utilized six days of historical data to forecast wellhead pressure trends. This enabled timely interventions based on pressure curve anomalies. The model was validated in the Loma Campana control room and provided hourly anomaly probabilities. Data cleaning was emphasized as crucial, and the LOESS algorithm and a Tukey test were used for time series decomposition and outlier detection, respectively.

In a related study, Delgado focused on optimizing coiled tubing (CT) operations in Vaca Muerta, addressing challenges like casing collapse during hydraulic fracturing. The study spanned 45 wells across 12 pads and aimed to enhance operational efficiency without compromising safety or environmental standards. Key performance indicators (KPIs), such as CT speed and plug milling time, were systematically introduced in order to improve operations. The study also discussed the impact of various factors like CT pipe weight and fluid resistance on these KPIs. Overall, the optimization efforts led to an 11% reduction in total well time during frac plug mill-out operations.

Additionally, the study explored the optimization of CT string designs and emphasized the critical role of fluid management. It also discussed how elevated temperatures in the fluid system can adversely affect the rheological properties of additives, leading to excessive CT pressure.

9.4. Well Spacing Stimulation Design Optimization

To optimize both estimated ultimate recovery (EUR) and cost efficiency, it is crucial to fine-tune well spacing and stimulation parameters. The optimization process encompasses petrophysical and geomechanical assessments, hydraulic fracturing simulations, and reservoir modeling. In the last ten years, there has been a shift in stimulation strategies from using more viscous fluids and broader cluster intervals to adopting less viscous fluids with narrower cluster spacing.

Malhotra et al. conducted an optimization study, focusing on well stimulation parameters such as proppant and fluid volumes, cluster intervals, and fluid categories. Some wells employed high-density completion (HDC) strategies, which involved increased proppant and fluid volumes, along with reduced cluster spacing. Cloud-based computational resources facilitated the parallel execution of numerous simulations. Extensive data collection efforts were undertaken to gauge well performance, incorporating metrics like liquid tracers, production pressures, and treatment pressures. A design of experiments (DoE) approach was employed to assess the influence of well spacing and stimulation parameters. Utilizing cloud computing, the analysis reduced the computational time from three months to one week. The optimization process led to a 50–100% increase in estimated ultimate recovery (EUR) and a 10–30% reduction in per-unit development costs [78].

9.5. Economics Consideration during Optimization

During the optimization of life-cycle development, the cost of drilling and completion dominates the expense profile of the Vaca Muerta wells. Innovations such as walking rigs and the optimization of drilling practices have contributed to substantial cost reductions, from $16 million per well in 2014 to approximately $8 million, halving the investment needed for well development. The formation has attracted steady investment, with capital expenditure forecasted to rise significantly. The average breakeven price of $40/bbl for oil and $5.5/mcf for gas positions Vaca Muerta competitively with other global unconventional plays. The internal rate of return (IRR) and net present value metrics indicate a positive economic outlook for projects within the formation [79].

10. Potential Issues

In the process of installing artificial lift systems within the El Trapial sector of the Vaca Muerta, the presence of both corrosion and scaling was detected across disparate well pads (Figure 12). The corrosion phenomena were principally concentrated in the inferior segment of the tubing string and were linked to elevated levels of CO_2 partial pressure, as well as the production of acidified water. Analytical verification revealed that the scale deposits predominantly consisted of barium sulfate ($BaSO_4$). Both of these issues pose a significant threat to the structural integrity and operational performance of the well [80,81].

Figure 12. Tubing corrosion in the Vaca Muerta formation. Reprinted with permission from Ref. [80]. Copyright 2014, Society of Petroleum Engineers.

Fluidic assays demonstrated that the accumulated deposits chiefly contained elements of calcium, barium, and strontium, along with specific concentrations of CO_2, water pH levels, and samples of suspended particulates. Notably, heightened levels of $BaSO_4$ and $SrSO_4$ were documented.

In an effort to counteract the scaling complications, the operations team adhered to customized Scrum methodologies and conducted five two-week sprints. During these periods, they carried out simulations of fluid flow rates across varied tubing dimensions, examined corrosion velocities, developed drawdown tactic models, and scrutinized both the lead times and the cost increments for necessary materials. From a metallurgical perspective, a transition was made to tubing that was composed of chrome alloy as opposed to carbon steel. Financial estimates indicated that the utilization of tubing with a 3%

chromium content would necessitate an additional four-month lead time and would incur costs approximately 35% higher than those associated with carbon steel tubing.

Field trials were initiated using tubulars made of 3% and 13% chromium alloys since 2020. Comprehensive surveillance protocols were implemented, incorporating advanced sensor systems and periodic multi-finger caliper inspections. These measures have been instrumental in formulating a production approach that mitigates corrosion-related failure risks and enhances the reliability of downhole equipment throughout its operational lifespan.

The scaling problem stems from unique brine chemistries, which contain high concentrations of calcium, barium, and iron [82,83]. These ions pose a significant risk when they interact with bicarbonate and/or sulfate in the fracturing fluids or produced water, leading to the formation of calcium carbonate and/or barium sulfate scales. Based on North American practice, copolymer and phosphate ester scale inhibitors, which have shown good control over barite scaling in the presence of iron, have also been applied in the Vaca Muerta production systems [84,85]. Spicka et al. emphasize the importance of 'cradle to grave' scale management, which includes the careful selection of fracturing fluids, scale inhibitors, and monitoring practices to optimize chemical programs and mitigate the challenges associated with scaling in Vaca Muerta [86].

The formation's unconventional oil and gas resources are notable for their potential to increase the supply of affordable and reliable oil, while aiming to reduce global greenhouse-gas intensity. This is particularly relevant as the oil and gas industry faces increasing pressure from societal, policy, and investor stakeholders to shift towards cleaner energy sources and set ambitious net-zero emissions targets. Fortunately, according to the public data, the carbon intensity of oil production from Vaca Muerta is among the lowest globally, standing at 15.8 kg of CO_2 per barrel of oil equivalent (BOE), which is well below the global average. This lower carbon intensity means that the increased production and export from Vaca Muerta could contribute to reducing the intensity of global greenhouse gas emissions, aligning with the industry's transition towards more sustainable practices [87].

11. Conclusions

We reviewed recent development of the Vaca Muerta formation in this article, which can be structured around the following five key points:

- In terms of geological characterization, the Vaca Muerta formation's geological analysis reveals significant hydrocarbon potential, with TOC values ranging from 3% to 8%, indicating rich organic content. The formation varies in thickness (60–520 m) and exhibits diverse porosity (4–14%), emphasizing its complexity.
- Technological advances in drilling has shown the shift to horizontal drilling, with laterals extending 2500–2800 m, and even up to 4000 m in some projects, marking a significant advancement. This approach, despite challenges in wellbore stability and tortuosity, has led to improved production efficiency.
- Hydraulic fracturing innovations include the application of tailored fracturing fluid compositions and injection protocols, based on reservoir conditions, has optimized fracturing processes. The use of polyacrylamide-based viscosifying friction reducers in some regions has reduced operational costs by 34%.
- Regarding economic considerations and investment, the formation continues to attract significant investment, despite high operational costs due to logistical constraints. The decrease in extraction costs and the introduction of efficient technologies have enhanced its global competitiveness.
- Future prospects and challenges are revealed. Projected advancements in technology and favorable policy shifts could significantly increase the formation's contribution to global hydrocarbon production. Continued research and development are essential to overcoming the operational and environmental challenges.

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