SOCAR Proceedings

Reservoir Engineering

journal home page: http://proceedings.socar.az

HYDRAULIC FRACTURING IN TIGHT OIL RESERVOIRS: A SYNTHESIS OF CURRENT PRACTICES, CHALLENGES, AND FUTURE TRAJECTORIES

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ABSTRACT

Multistage hydraulic fracturing (MHF) is the primary method for developing extremely tight oil reservoirs (TORs) with nanopores. Currently, this technology is considered the only economically viable way to develop these resources. However, MHF suffers from geomechanical limitations, including formation heterogeneity and limited pumping capacity at surface facilities. This paper reviews the current state of MHF in tight oil reservoirs, connecting geomechanical concepts to field applications and highlighting key challenges and future trends, including sustainability and digital transformation. The industry has evolved from simple planar fracturing operations to complex stimulated reservoir systems (SRS). Modern design is based on geological characteristics; in-situ stresses and natural fractures guide engineering decisions, such as the use of hydraulic fracturing fluids. However, this sector faces ongoing challenges, including overlap of parent and child wells, low recovery factors (less than 10%), and loss of conductivity, caused by gaps in the scaling of complex physical processes across time and space. Addressing these challenges is facilitated by digitalization. By harnessing data analytics, ML and real-time DAS/DTS, operators transition from a «design and pump» paradigm to a «sense and respond» approach. This empowers them to optimize real-time hydrocarbon sweep and bridge key sustainability gaps. In conclusion, this review illustrates how optimized water management, efficient operational scaling and sustainable design in MHF directly contributes to SDGs 6, 8, 9 and 12, promoting responsible global resource stewardship.

Keywords: tight oil reservoirs; hydraulic fracturing; stimulated reservoir system; fracturing fluids; energy efficiency; sustainable energy; clean energy technology.

Date submitted: 13.08.2025 **Date accepted:** 28.04.2026

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1. Introduction

TORs are unconventional hydrocarbon formation with ultra-low permeability and nano-sized pores [1]. These reservoirs have increasingly emerged as promising targets for oil and gas exploration and production in the future for replacing global conventional oil resources [2-4]. The matrix permeability of TOR is generally less than 1.0 mD, and some definitions may be as low as 0.1 mD or lower [5]. Such low permeability severely hinders fluid flow within the pores and the fractures in the reservoir, and making the conventional production difficult and requiring advanced recovery techniques such as hydraulic fracturing [6, 7].

2. The tight oil reservoir system

2.1. Petrophysical and fluid flow characteristics

In contrast to conventional reservoirs, the petrophysical constraints of TORs, specifically ultra-low matrix permeability [8] and nanopore confinement [9], make traditional recovery ineffective [10] and require extensive hydraulic stimulation to achieve commercial rates. Consequently, Multistage Hydraulic Fracturing (MHF) in horizontal wells has become the standard development strategy, driven by the engineering and economic factors detailed in table 1.

2.2. Geomechanical controls on fracture propagation

Table 2 summarizes how geomechanical factors influence fracture geometry and conductivity.

In TORs, the in-situ stress field defines macro-scale fracture orientation, whereas rock fabric and natural fracture topology drive the non-linear development of micro-scale complexity and the resulting stimulated reservoir system (SRS).

Operators target 'geomechanical sweet spots', characterized by high brittleness and low stress anisotropy, to induce

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http://dx.doi.org/10.5510/OGP20260201199

shear slippage and enhance network complexity. Using diagnostics (e.g., dipole sonic, DFIT) to accurately map these variations allows operators to optimize landing zones and pumping schedules for maximum reservoir contact.

Following the clarification of the main geological and geomechanical factors that define the fracture propagation, the next logical step is the study of how these complex interactions can be represented in predictive modelling systems. This leads to the optimization of fracture design, starting with the need for reliable prediction of fracture geometry.

Table 1

Core attributes of TORs and their implications for development

Key Attribute / Domain	Description	Engineering/Economic Implication
Petrophysics & Fluid & Flow	• Rock permeability < 0.1 mD makes production negligible without stimulation [11, 12]	• Economic production requires creating an extensive network of high-conductivity fractures [13, 14]. • Hydrocarbons are confined within nanopore structures, which necessitates dense fracture spacing and high-pressure gradients to initiate flow [15, 16].
Geology & Geomechanics	• Heterogeneity creates complex fracture networks [17-20].	• Enabling SRS design to maximize reservoir contact [21]
Production and development	• Transient flow dominates produc-tion, causing steep declines and low recovery. Economic success relies on effective initial hydraulic fracturing to maximize SRS [22, 23].	• Economic success depends on effective initial hydraulic fracturing to generate an extensive SRS [24], pairing horizontal drilling and MHF has become the standard execution strategy for tight oil development [25, 26].
Economic & Sustainability Context	• The vast scale of tight oil resources has altered global markets.	• Creating immense economic incentive to optimize the fracturing process [24] and driving innovation in sustainable practices like water management [25].

Table 2

Controlling geological and geomechanical factors

Controlling factor	Description	Implication for fracture propagation
The in-situ stress state	The stress field is defined by three orthogonal stresses: vertical σ_v, maximum horizontal $\sigma_{h\max}$, and minimum horizontal $\sigma_{h\min}$ [27]. Key metrics are: 1. Magnitude of $\sigma_{h\min}$ 2. Horizontal stress anisotropy ($\sigma_{h\max}$-$\sigma_{h\min}$)	• A hydraulic fracture propagates along the path of least resistance, opening perpendicular to $\sigma_{h\min}$. Consequently, the in-situ stress orientation controls the primary fracture azimuth [27]. • The magnitude of $\sigma_{h\min}$ represents the pressure required to be overcome fracture initiation and propagation. • High Anisotropy: Strongly favors a single, planar, bi-wing fracture [28]. • Low Anisotropy: Promotes a complex, multi-stranded fracture network by enabling interaction with natural fractures [29, 30].
Rock mechanical properties and fabric	Key properties include: • Brittleness vs. ductility: The tendency of the rock to fracture (brittle, e.g., quartz-rich) versus deform (ductile, e.g., clay-rich) [29, 31]. • Fracture toughness: The rock›s resistance to fracture propagation [31]. • Rock fabric (heterogeneity): Internal structures like laminations, bedding planes, and mineralogical variations [32-34].	• Brittle rocks support the creation of intricate, stable fracture networks. Ductile rocks consume energy by deforming, leading to less effective fractures [29, 31]. • Laminations and bedding planes act as mechanical interfaces that govern fracture geometry by arresting, diverting, or bifurcating propagation [35, 36].
The role of natural fracture systems	• Pre-existing fractures (open, cemented, or healed) that are common in many TORs [29, 31]. • The SRS is the final, interconnected network of engineered hydraulic fractures and reactivated natural fractures.	• The interaction between the hydraulic fracture and the natural fractures is the primary driver of network complexity. • A hydraulic fracture can be arrested by cross, dilate (open), or reactivate (shear) a natural fracture. • Dilation and reactivation create pathways that deviate from the stress-field-preferred direction, maximizing the size and connectivity of the SRS [30, 31]

3. Hydraulic fracture modeling: from analytical to complex numerical

Fracture design must be made with geometric predictions. Modeling has evolved from poorly developed analytic tools to sophisticated numerical simulators that reproduce complicated geomechanical processes [37]. The exact usefulness of these processes is questioned in the current TORs exploration context.

3.1. Early analytical and 2D models

The Perkins–Kern Nordgren (PKN) and Khristianovic-Geertsma-de Konings (KGD) models have historically been the basic analytical model of two-dimensional fracture design. The models of the fluid-rock interaction are defined with specific geometric restrictions, i.e., the KGD representation assumes the vertical aperture is constant, and thus opens wider hydraulic apertures compared to the elliptical pore geometry derived in the PKN representation [38, 39]. Although quite computationally expedient, the applicability of these two-dimensional models to real-life operatoring reservoirs (TORs) is limited. Their natural presupposition of a single, planar bi -wing fracture in a uniformly isotropic medium excludes the proper modeling of the multi-dimensional interplays of existing natural fractures which are essential in engineering a Stimulated Reservoir System (SRS).

3.2. Pseudo-3D (P3D) models

Pseudo-3D (P3D) models were developed as an intermediate step, offering an efficient compromise between 2D simplicity and fully 3D complexity. P3D models retain a simplified 2D representation of fluid flow and proppant transport along the fracture's length but introduce a third dimension: fracture height growth [40]. These models allow the fracture height to vary along its length, with growth being constrained by vertical variations in in-situ stress and rock properties across different layers [41]. This capability enabled the prediction of vertical containment, allowing engineers to simulate fracture containment within a target zone bounded by higher-stress barriers, a consideration for avoiding water zones or non-productive rock [40] .

The primary advantage of P3D models is their computational efficiency, making them significantly faster than fully 3D models while still capturing first-order effects of layered geology [40]. However, their underlying assumptions also introduce limitations. By simplifying the rock mechanics to a state of plane-strain elasticity, P3D models can be prone to inaccuracies, particularly in highly heterogeneous formations [40]. Most importantly, they are based on the assumption of a single, planar fracture and cannot simulate the complex network development central to stimulating most TORs [42].

3.3. Advanced numerical and complex fracture models

The shift toward Stimulated Reservoir System (SRS) required fully 3D models (table 3) capable of simulating coupled physical processes in naturally fractured reservoirs.

Modern numerical modeling provides a suite of specialized tools, each with distinct strengths. Model selection is driven by the dominant geological concern: DFN and DEM when natural fracture interaction and shear failure are dominant, or FEM and XFEM when consideration of stress evolution and complex propagation paths in the rock matrix are of interest. Advanced workflows often involve hybridized or coupled approaches (e.g., to the finite element analysis (FEM) to model the far-field stress response while at the same time using Discrete Fracture Network (DFN) or Discrete Element Method (DEM) models to capture near-fracture information. Despite their computational requirements, these models are necessary in the accurate representation of geological reality.

The resultant simulations are used to make specific field decisions, which are mostly to reduce the well interference and the selection of fluids, proppants, and completion equipment.

Table 3

Key advanced numerical models for complex fracture simulation

Model / Approach	Core principle & Description	Primary application and strength in TORs
Discrete fracture network (DFN) models	Simulates hydraulic fracture propagation through a pre-defined natural fracture network, calculating interactions like crossing, arrest, or reactivation [43, 44].	Predicting SRS geometry (size, shape, connectivity) where natural fracture reactivation is the dominant mechanism for creating complexity [45, 46].
Finite element method (FEM)	A continuum mechanics approach that discretizes the reservoir into a mesh of elements. It solves for stress, strain, and deformation throughout the rock matrix as a result of fracturing [47].	Excellently suited for modeling stress shadowing effects and the mechanical response of the rock matrix surrounding the fractures. It provides the geomechanical framework for fracture interaction [48].
Extended finite element method (XFEM)	An enhancement of FEM that allows discontinuities (fractures) to be modeled independently of the mesh. Fractures can propagate along arbitrary paths without requiring computationally expensive remeshing [49].	Ideal for modeling non-planar fracture growth and propagation in complex stress fields or heterogeneous rock where the fracture path is not known in advance [50].
Distinct/Discrete element method [51]	Models rock as discrete blocks or particles, directly simulating their interaction, rotation, and failure [52].	Excels at simulating hydraulic-natural fracture interactions, specifically modeling shear slippage and arrest as functions of the intersection angle relative to maximum horizontal stress [53].

4. Modern fracture design, execution, and well interference

Hydraulic fracturing bypasses the ultra-low permeability of TORs by creating high-conductivity fractures through the injection of fluid and proppant (table 4).

Field execution depends on successful apply of geomechanical models to engineering practice. The objective is to generate a stable, highly conductive SRS that maximizes hydrocarbon recovery. This requires optimizing the fluid selection, proppants schedules, and the operational sequencing, particularly in multi-well pads where interference is a dominant factor.

4.1. The design-execute-analyze workflow

Following the completion of the design, the operational aspect, as well as the post-treatment diagnostic analysis become the main focus. This cycle of analysis connects the design process to the results, thus optimizing both well performance and field development, as shown in table 5.

4.2. Fracturing fluids: the shift to slickwater

Legacy gels have advantages regarding proppant transport, but slickwater systems are preferred for their lower cost to create SRS, despite issues associated with water sensitivity (table 6).

Table 4

Foundational aspects of modern hydraulic fracturing treatments in TORs

Aspect / Domain	Core Principle / Mechanism	Key Implications & Innovations
Core process & objective [54, 55]	Enhances reservoir flow capacity by injecting fluid at pressures exceeding the rock›s tensile strength and minimum in-situ stress	Propping agents (e.g., sand) are transported by the fluid to maintain fracture aperture after pressure release, creating a durable flow path
Enabling technology integration [7, 25, 56]	The synergistic integration of Multi-Stage Hydraulic Fracturing (MHF) with long-reach horizontal drilling	Horizontal wellbores provide access to vast reservoir sections, while MHF generates the massive surface area required to overcome ultra-low matrix permeability
Technological evolution & optimization [57]	A shift from standardized «manufacturing» treatments to highly engineered, geology-driven designs	MHF allows for precise, repeated stimulation to maximize contact. Tailored Designs utilize specialized additives and tracers to diagnose effectiveness and mitigate issues like flowback
Operational & sustainability context [58]	The immense operational scale imposes significant logistical hurdles and environmental risks, particularly regarding water usage	High water usage drives recycling innovation (SDGs 6, 9, 12), while induced seismicity risks mandate rigorous wellbore integrity and regulatory compliance

Table 5

Key phases of the fracture execution and optimization workflow

Phase	Core objective and activities	Key considerations and analytical tools
Planning & design	Develop a plan aligning engineering with geological and economic targets, including reserve estimation and fracture modeling [59, 60]	Must account for equipment limits and completion hardware configurations (e.g., packer spacing, perforation clusters) [59, 61]
Field execution	Safely execute the pumping schedule to deliver fluids and proppant to target zones efficiently [59, 62]	Requires real-time pressure monitoring and adherence to design; deviations (e.g., screen-outs) must be documented for analysis [59]
Post-fracture analysis & optimization	Evaluate treatment effectiveness and diagnose issues to refine future designs for continuous improvement [59, 63]	Uses diagnostics like spectral noise logs (SNL) and temperature modeling to assess zonal isolation and fracture initiation [64]

Table 6

Comparison of fracturing fluid systems for TORs

Feature	High-viscosity crosslinked gels (legacy approach)	Low-viscosity slickwater (modern standard)
Primary advantage	Excellent proppant transport capability [65]	Cost-effective and promotes the creation of complex fracture networks [66]
Cost-effectiveness	High, due to complex polymer chemistry [67]	Low, primarily consisting of water and small amounts of friction reducer [68]
Formation damage risk	High, due to potential for unbroken polymer residue [69]	Low solid residue damage in hydraulic fracturing, poses a significant formation damage risk in TORs, primarily due to water sensitivity [70]
Fracture complexity	These fluids typically create simple, wide, bi-wing fractures because they effectively maintain fracture width. However, this same capability inhibits the formation of complex fracture networks [71]	High, as the low viscosity allows the fluid to easily penetrate and activate pre-existing natural fractures, generating a complex SRS [72]

4.3. Proppant selection and transport challenges

Stimulation efficiency depends on selecting proppants strong enough to withstand closure stress. The selection involves a trade-off between transport capability, embedment risk, and environmental requirements.

Sand is preferred due to its lower cost and availability. However, for high closure stress in deeper wells, sand will break into smaller particles. This results in a reduction in its conductivity. For instance, the conductivity for 30/50 and 40/70 mesh sand reduces by 36.6 and 45.5 %, respectively for high [73, 74]. Ceramics, made of either bauxite or kaolin, will most often support extreme stresses, and in general, they maintain conductivity much more consistently than sand. The problem with ceramics is that they are heavier, their transport to the fracture requires either thicker fluids or faster pumping. That means extra effort in operations and whether it pays off is a subject of dispute [73].

Embedment further decreases conductivity because it allows the fracturing face to devour the proppant. This problem is usually dealt with using resin-coated proppants which not only reduce embedment, but also inhibit fines migration [75].

Effective proppant transport is essential to ensure fracture connectivity. Conventional proppants settle rapidly in slickwater, leading to poor placement. Ultra-lightweight proppants (ULWPs) address this limitation with near-neutral buoyancy, enabling efficient transport even in low-viscosity fluids [75, 76]. Although these lower-density materials transport easily, they often lack the compressive strength required for high-stress environments [76, 77].

From an environmental and health perspective, there are two issues that should be considered. First, treatment and transport of proppants, particularly sand, can generate a large amount of dust, posing a health hazard for the workforce. Appropriate dust control practices and the use of less harmful proppants can help avoid this issue [78, 79]. Second, certain proppants, dependent on geographic origin, can contain naturally occurring radioactivity which must be properly handled and disposed of in an appropriate manner to ensure regulatory compliance [78].

A selection of the proppant material must be made, as it involves a trade-off between cost and performance in order to identify the most suitable option (table 7 provides a comparison of sand and ceramic proppants).

In summary, the selection between sand and ceramic proppants is a compromise among cost, strength, conductivity and shipping challenges. Ceramic proppants have the highest performance and strength in these high-performing environments (an increased price, and transport costs are not included). Sand, although it requires greater exertion to compensate for its shortcomings, has proven to be a cost-effective alternative for more modest requirements.

4.4. Completion strategies and hardware

The primary completion strategies employed to execute multi-stage hydraulic fracturing in TORs, along with their objectives and key considerations, are detailed in table 8.

Table 7

Comparative analysis of sand and ceramic proppants

Aspect	Sand proppants	Ceramic proppants
Cost	Low	High
Strength	Adequate for shallow wells	High, suitable for deep wells
Conductivity	Lower, especially under high stress	Higher, maintains conductivity under stress
Density	Lower, easier to transport	Higher, requires higher fluid viscosity
Environmental Impact	Higher fugitive dust/health risk	Lower dust risk; potential for naturally occurring radioactive materials
Embedment	Prone to embedment	Less prone, can be mitigated with treatments

Table 8

Comparative analysis of modern completion strategies

Completion strategy	Core principle & objective	Key advantages	Challenges & key considerations
Plug-and-perf method	Utilizes a cemented casing perforated at desired locations to achieve precise control over fracture initiation points [80]	• Precise control of fracture initiation [80] • Effective in high-pressure environments [81]	• Requires multiple wireline runs for plugs and perforating guns [81] • The cost of plugs and operations can be significant [82] • Involves setting plugs to isolate stages and perforating to create entry points [81]
Cluster spacing optimization	A design philosophy that uses shorter spacing and more clusters per stage to enhance stimulation performance and economic outcomes [83]	• Improved initial production [83]. • Enhanced reservoir contact [83]	• Optimal spacing is highly dependent on specific reservoir characteristics [83]. • Early production may be compressed with potentially similar long-term recovery [84]
Limited entry design	Controls fluid flow by creating a limited number of entry points (perforations), forcing fluid to be distributed more evenly among clusters [85]	• Cost-effective [85]. • Reduced operational risks [86]	• Relies on effective isolation to direct fluid as intended [87] • The number and size of perforations must be meticulously engineered to achieve the desired pressure drop and fluid distribution [88]

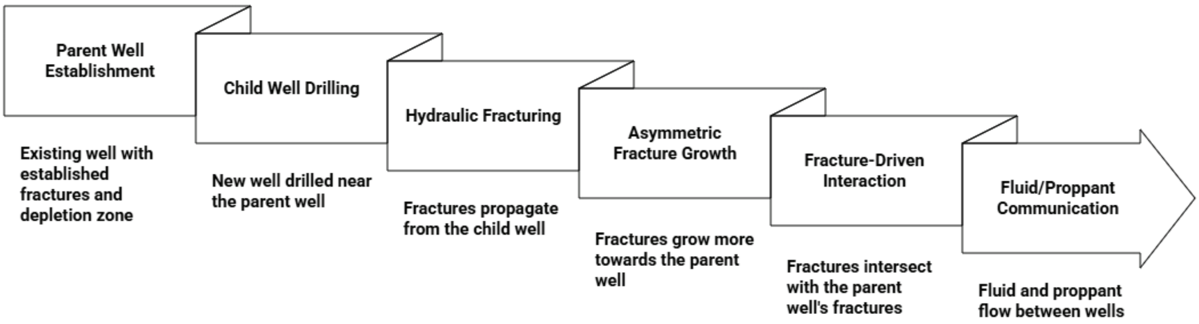

Fig. 1. Managing frac-driven interactions (FDIs) in TORs

Table 9

Governing Mechanisms of FDIs between parent and child wells

Mechanism	Core principle & geomechanical driver	Consequence & impact on well performance
Pore pressure alteration	Parent well depletion creates a low-pressure «sink,» preferentially attracting high-pressure child well fractures [89]	Fractures grow asymmetrically toward the parent, causing over-stimulation of the depleted zone and under-stimulation of the child well's far side [90]
Stress field redistribution	Poroelastic pressure drops reduce local horizontal stress, creating a «path of least resistance» that alters fracture propagation direction	Fractures deviate from the regional trend, bending into the parent well›s altered stress field and reducing stimulation effectiveness[90]
Direct fluid & proppant interference	Child well fractures physically intersect the parent well's existing network or wellbore	The parent well suffers a sudden influx of fluid and proppant («frac hit»), causing water loading, cleanout issues, or casing failure [89]

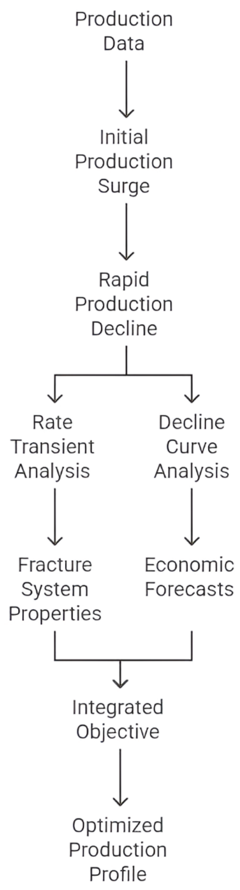

Fig. 2. Production data analysis for fracture characterization

Table 8 suggests that a successful modern hydraulic fracturing treatment requires a battery of primary completion strategies which all have their own advantages and disadvantages. The Plug-and-Perf provides superior zonal isolation, but its operational complexity has driven a shift toward Limited Entry strategies that use fluid dynamics for simultaneous stimulation. This efficiency risks may result in uneven cluster distribution due to stress shadowing and erosion. Thus, strategy selection is governed by geomechanics, balancing reservoir contact against the need for positive isolation.

4.5. Hydraulic fracturing in TORs: parent-child well interference

For mature TORs, one of the main issues is coping with Frac-Driven Interactions (FDI) during the stimulation phase. This is caused by the proximity of the parent and child wells, hence the resulting hydraulic/poroelastic connectivity. Figure 1 below shows the processes discussed above and their mitigation techniques.

Table 9 summarizes the primary drivers of frac-driven interactions.

Optimization relies on quantitatively linking stimulation parameters to production outcomes, which serve as the definitive metric of success.

5. Performance evaluation from production data

The ultimate measure of a hydraulic fracturing treatment's success is the well's production performance. Far-field diagnostics characterize geometry, but the analysis of production rates and pressure transients is required to quantify the economic outcome. The characteristic production signature of fractured wells drilled in TORs (fig. 2) provides the data necessary to quantify economic outcomes.

5.1 The characteristic production signature of fractured wells

Hydraulically fractured horizontal wells in TORs are defined by a distinct and predictable production profile: a period of very high initial production followed by a steep, multi-year decline. This distinct profile—high initial production followed by steep decline—is detailed in table 10.

As detailed in table 10, the characteristic production signature of a fractured tight oil well is a direct reflection of the underlying physics of the system created by the stimulation. The initial production surge is not a property of the reservoir itself, but rather a manifestation of the vast, highly conductive fracture surface area engineered during the treatment. The resulting rapid decline, conversely, is not due to wellbore failure, but is the unavoidable result of a transient flow response, as the finite, high-drainage volume near the fractures is depleted. The production profile results from the interaction between engineered fracture properties and the native reservoir permeability. Consequently, production data serve as a clear diagnostic of the stimulation success.

5.2 Production data analysis for fracture characterization

Production decline curves serve as a primary diagnostic dataset. Table 11 outlines the analytical techniques used to interpret this flow data and infer fracture geometry.

Production data analysis serves dual roles: diagnosing fracture properties [104] and forecasting recovery (DCA). Integrating these insights establishes a quantitative feedback loop, allowing operators to optimize future fracture designs by linking engineering execution directly to production performance.

6. Key challenges and underlying knowledge gaps in tight oil development

Even with the current success of horizontal drilling and MHF, the maximum performance is still limited by two technical issues: interference between wells and low recovery factor. This challenge is not just due to operational reasons, but is also because of the gap in our scientific understanding and our ability to predict. For example, long-term performance prediction of a large number of wells operating as one system requires understanding of complex non-linear coupled processes such as geomechanics, fluid flow and geochemistry. Intensive research is required in the industry to move forward in understanding geomechanical processes, fluid flow processes, and geochemical processes to overcome the knowledge gaps shown in figure 3.

Table 12 provides a comprehensive synthesis of these relationships, directly linking the primary practical challenges faced in the field today with the key scientific questions and research gaps that must be addressed to overcome them.

Table 10

Production signature of hydraulically fractured wells in TORs

Production phase	Description	Governing mechanisms and physical drivers
Initial production surge	Wells exhibit very high initial production rates immediately following stimulation, establishing the economic viability of the project [91]	• The primary objective of hydraulic fracturing is achieved, creating an immense network of fractures that acts as a super-highway for fluid flow to the wellbore [21]. • Dominated by the rapid drainage of hydrocarbons stored within and immediately adjacent to the high-conductivity fracture faces [21]
Rapid production decline	Characterized by initial high rates followed by a characteristically steep or dramatic decline[92]	• The finite, high-deliverability volume near the fractures is quickly depleted. Production becomes limited by the much slower transient flow of oil from the ultra-low permeability matrix into the fracture system [92] • Long-term productivity can be impaired by reduced near-fracture permeability due to adverse fluid-rock interactions [93] or by a loss of fracture conductivity from proppant crushing and embedment [94]

Table 11

Production signature of hydraulically fractured wells in TORs

Analytical technique	Description and purpose	Key Diagnostic Signature and Interpretation
Rate transient analysis, RTA	Uses log-log rate-pressure plots to identify flow regimes, diagnosing fracture geometry and stimulation effectiveness [95]	Identified by a ½ slope on log-log plots, signifying high-conductivity linear flow [96]. Duration correlates directly to total effective fracture surface area [97]
Decline curve analysis, DCA	Extrapolates historical production trends to forecast future performance and Estimated Ultimate Recovery (EUR). Translates physical reservoir behavior into economic valuation [92]	Decline Parameters (e.g., b-factor, Di): Unconventional wells typically exhibit hyperbolic decline (b>1) due to prolonged transient flow. These parameters quantify the decay rate and the transition from infinite-acting to boundary-dominated flow [98, 99]
Integrated objective	Establishes a feedback loop using RTA/DCA integration to optimize future fracture parameters based on quantified performance [100, 101]	Optimized profiles feature maximized initial rates and extended linear flow; a shallower decline confirms effective SRS connectivity and delayed boundary interference [102, 103]

Table 12

Synthesis of key challenges and underlying knowledge gaps in modern tight oil development

Key challenge	Manifestation & field-level impact	Underlying knowledge gaps & key research questions
Parent-child well interference	• Asymmetric «child» well fracture growth («frac hits»)[105]. • Poor stimulation of the intended reservoir volume[106] • Production damage to the «parent» well from fluid/proppant loading[90]. • Sub-optimal capital investment and field drainage[107]	• 4D Stress Field Evolution: How can we accurately predict the dynamic evolution of the 3D stress tensor over time as a function of depletion? Current poroelastic models are often too simplified or computationally expensive for routine design [108]. • Fracture Re-orientation: What are the precise conditions that cause a fracture to deviate from the regional stress orientation and «bend» toward a low-pressure sink? [108]. • Complex Fluid Transport: What are the physics governing fluid and proppant transport into a low-pressure, prefractured, and potentially multiphase reservoir region?
Low primary recovery factor (<10%)	• Extremely steep initial production declines[16]. • The vast majority (>90%) of Original Oil In Place (OOIP) is left unrecovered[109]. • Economic viability is heavily front-loaded and dependent on maximizing initial production rates [16].	• Dynamic Drainage Volume: What is the true size, shape, and connectivity of the reservoir volume that is actually being drained (DRV) versus the volume that is merely stimulated (SRS)? How does this evolve over the life of the well? • Nanopore Fluid Dynamics: How do multiphase flow, phase behavior (bubble point), and high capillary pressures interact within nanoporous media to trap oil? • Wettability Alteration: How does the injection of massive volumes of water alter the in-situ wettability of the rock, and how does this change impact relative permeability and ultimate recovery?
Long-term fracture conductivity degradation	• Production rates decline faster than predicted by initial models [110]. • A gradual loss of well producti-vity over its lifespan [111]. • Reduced effectiveness of late-life artificial lift systems [112].	• Proppant Pack Mechanics: What are the long-term failure mechanisms of proppant packs under combined cyclic stress, high temperature, and geochemical attack (diagenesis)? How can we accurately model proppant crushing and embedment over decades? • Near-Fracture Geochemistry: What are the slow, long-term geochemical reactions between injected fluids, formation rock, and proppant that lead to pore-plugging minerals (scaling) or rock strength changes near the fracture face?
Operational & sustainability	• High freshwater consumption [113]; logistical challenges and costs associated with transport and the disposal of highly saline produced water [114]. • Felt seismic events linked to salt-water disposal (SWD) wells [115].	• How can we develop cost-effective desalination and organic removal processes for produced water to enable its reuse without impairing fracturing fluid performance? • What modeling frameworks are needed to translate fault mapping into quantitative, time-lapse predictions of slip potential during injection operations?

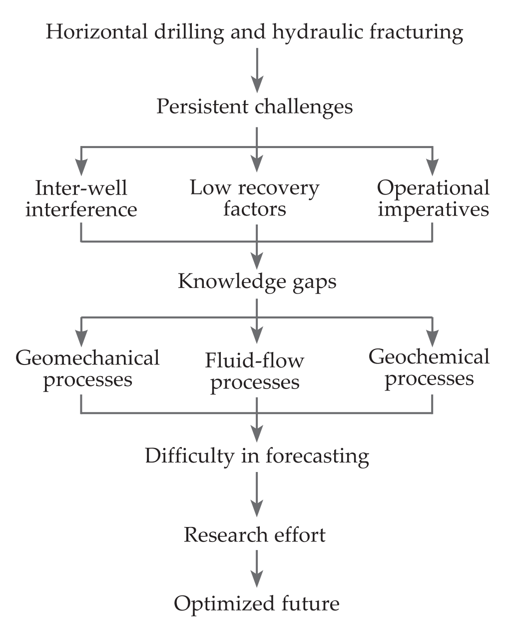

Fig. 3. Flowchart of key challenges, underlying knowledge gaps, and the path to an optimized future in tight oil development

7. Validating geomechanical and ai-based models in TORs: physical modeling and laboratory experiments

Physical modeling and laboratory-scale hydraulic fracturing experiments are required to validate geomechanical and AI-based frameworks in TORs [116-118]. Tools such as true triaxial stress frames, PMMA models, acoustic/fiber-optic monitoring, and high-temperature setups, provide high-fidelity data on fracture initiation, propagation, and complexity [116, 119-121]. These datasets are then used to calibrate geomechanical simulations through data assimilation like ES-MDA [122-124].

AI-based frameworks, leveraging deep learning architectures and ensemble methods, are trained and validated against laboratory and microseismic datasets, offering rapid, accurate predictions of fracture geometry, stimulated reservoir system, and production outcomes [117, 125-127]. Integration of multi-scale data, capturing the complexity of natural fractures, and correlating laboratory and field observations for AI training remain active areas of research and present challenges [128, 129].

Future research should focus on hybrid couple of Artificial intelligence and geomechanics, improved multiscale data integration, and advanced experimental validation techniques to further enhance predictive accuracy and operational control in hydraulic fracturing of TORs [116, 117, 130].

While numerical simulations can provide a wide range of problems, numerical models tend to be very general with constitutive laws that are oversimplified and cannot represent the full heterogeneity of TORs. Physical modeling complements the other experimental approaches and is used to collect ground-truth data for complex interactions. In large-scale true triaxial experiments, the physical simulation of 'parent-child' well scenarios is made possible by pre-fracturing a sample block (parent) and then fracturing a secondary wellbore (child) in different stress regimes. These tests are particularly relevant for validating 'stress shadow' effects and fracture re-orientation as forecast by AI models, to anchor digital tools in physical evidence and not just assumptions.

8. Future trajectories and research directions

8.1. The drive for optimization: data analytics and machine learning

Modern hydraulic fracture optimization shifts primarily from physics-based simulation alone to a hybrid approach that integrates vast operational datasets with machine learning [131] and artificial intelligence (AI)[132-134] as summarized in figure 4.

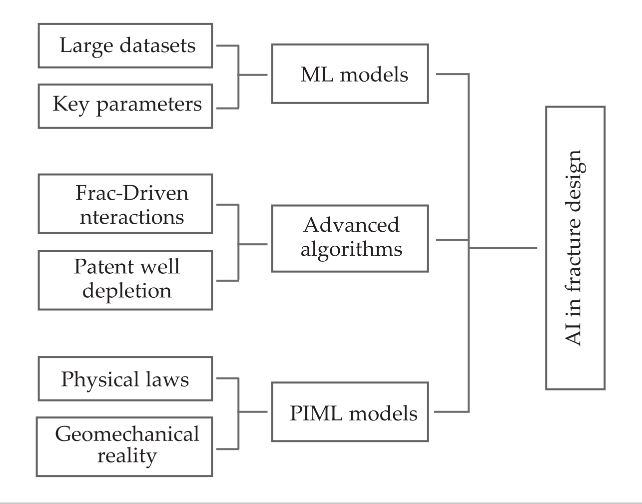

Fig. 4. Framework for artificial intelligence integration in hydraulic fracture design

8.2. Real-time diagnostics and automation

In-well fiber-optic tools, most notably Distributed Acoustic Sensing (DAS) [131] and Distributed Temperature Sensing (DTS), provide real-time information along the lateral. These tools provide information at the cluster scale, measuring the amount of fluid placed, the efficiency of slurry placement, and inter-well communication [135].

The ultimate goal of many of the diagnostics developed using high-resolution data is to bring the operation of fractured wells as close to fully automatic, feedback-controlled operation as possible. By using real-time DAS and DTS to steer algorithms that can detect inefficiencies and adjust pumping as it is happening, operators can shift from running a predetermined plan to performing a reactive-equivalent calibration process in real time.

8.3 Advancements in materials and sustainability

Parallel to the digital pivot, material innovations aim to reconcile stimulation performance with sustainability. Table 13 outlines key technological innovations and future trajectories in multistage hydraulic fracturing (MHF), mapping specific advancements to the primary operational or environmental challenges they aim to resolve.

Table 13

Future trajectories in fracturing materials and sustainable technologies

Innovation domain	Key technology / trajectory	Primary objective & addressed challenge/gap
Materials for enhanced performance	Ultra-lightweight proppants (ULWPs)	Enhances proppant transport in slickwater to ensure uniform distribution and effective fracture conductivity, addressing complex fluid transport gaps [76]
	Advanced surfactants & nanoparticles	Induces water-wetness to reduce capillary trapping forces, directly addressing the fundamental challenge of low primary recovery[136]
Technologies for improved sustainability	Advanced water treatment & recycling	Facilitates onsite water recycling, minimizing freshwater sourcing and deep-well disposal volumes to lower operational and environmental costs [114]
	Greener fluid chemistries	Minimizes environmental footprint by utilizing biodegradable polymers and non-hazardous fluid additives [137], less hazardous surfactants, and sustainable scale and corrosion inhibitors
	Waterless / Energized Fracturing Fluids	Substitutes water with CO_2 or N_2 to eliminate disposal-induced seismicity risks, though currently constrained by high operational costs [138]

Conclusions

1. Hydraulic fracturing is required to produce tight oil. At first, hydraulic fracturing was executed essentially by means of brute force techniques. With the advancements in technology, it has now evolved into a very sophisticated science-based method of generating energy products from hydrocarbons. The provision for long horizontal drilling together with MHF now makes it possible for hydraulic fracturing to be transformed completely; going from creating straight flat planar fractures to more structured designs using SRS and managing the hydraulic fracture from both a geo-mechanical as well as fluid dynamics perspective.
2. Modern fracturing relies on a geology-driven approach where quantified geomechanics dictate treatment design. Optimization must extend to the field scale to mitigate parent-child interference, utilizing production data analysis (RTA/DCA) as the essential feedback loop for continuous improvement.
3. Integrating AI and fiber-optic diagnostics (DAS/DTS) addresses critical knowledge gaps in upscaling coupled physics, targeting low recovery and well interference. This drives the industry toward a dynamic ‘sense and respond’ paradigm, enabling real-time automation to maximize both production and sustainability.

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