ENVIRONMENTAL REPORTS

Review Article
ISSN: 3041-556X
Journal homepage: https://er.researchfloor.org/

Petroleum Geology of Unconventional Reservoirs: A Review of Current Research

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Citation: Sarah Itohan Aduwa, Moses Adondua Abah, Michael Oladosu Abimbola, Ochuele Dominic Agida and Chibuzo Joseph Attah (2025). Petroleum Geology of Unconventional Reservoirs: A Review of Current Research. *Environmental Reports; an International Journal*. **DOI: https://doi.org/10.51470/ER.2025.7.2.190**

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Received 19 August 2025 | Revised 11 September 2025 | Accepted October 09 2025 | Available Online November 06 2025

ABSTRACT

The increasing global demand for energy has led to a shift in focus towards unconventional reservoirs, which have become a vital component of the global energy mix. Unconventional reservoirs, such as shale gas, tight oil, and coalbed methane, require advanced technologies and complex exploration and production techniques to extract hydrocarbons. Despite the challenges, these reservoirs have revolutionized the energy landscape, with many countries experiencing significant increases in production. However, the geology of unconventional reservoirs is complex, and understanding the characteristics of these reservoirs is crucial for optimizing exploration and production. Recent advances in drilling, completion, and stimulation technologies have improved the efficiency and economics of unconventional reservoir development. A comprehensive review of current research on the petroleum geology of unconventional reservoirs is essential for understanding the current state of knowledge and identifying areas for future research. This review highlights the complexities of unconventional reservoirs and the need for advanced technologies to optimize exploration and production. Key findings include the importance of understanding reservoir characteristics, fluid flow mechanisms, and the role of drilling and completion techniques in improving efficiency. In conclusion, unconventional reservoirs will continue to play a vital role in the global energy mix, and further research is needed to overcome the challenges associated with their development and ensure sustainable energy production.

Keywords: *Petroleum, Reservoir, Energy, Sustainable, and Efficiency.*

Introduction

Unconventional reservoirs have become a defining frontier in global hydrocarbon exploration, reshaping how geoscientists understand petroleum systems and hydrocarbon resource potential [1]. As conventional fields mature and production declines in many basins, the development of unconventional plays such as shale gas, tight oil, coalbed methane, and oil sands has become critical to sustaining energy supply [2]. These reservoirs differ fundamentally from conventional accumulations because their production depends on complex nano- to micro-scale pore systems and extremely low permeability that require stimulation to release hydrocarbons [3]. Their rapid commercial expansion, particularly in North America, demonstrates the combined effect of geological understanding, engineering innovation, and policy support. However, this transformation also calls for a systematic review linking source-rock processes, reservoir characteristics, and field-scale behaviour to exploration and production strategies [4].

In unconventional systems, geological controls operate across multiple scales, from regional basin frameworks to microscopic pore geometries [5]. At the basin scale, factors such as total organic carbon (TOC), kerogen type, thermal maturity, and burial history control hydrocarbon generation and expulsion potential [6]. Within the reservoir, mineral composition, rock fabric, and natural fractures determine pore connectivity, permeability, and hydrocarbon storage [7].

Nano- and micro-pores within organic matter act as both source and reservoir spaces, where gas is stored in adsorbed and free states [8]. This hierarchical system of geological and petrophysical parameters requires integration of basin modeling, core analysis, and nano-scale characterization to accurately predict reservoir quality and productivity [9].

Advances in characterization technologies have enhanced the ability to describe and model unconventional reservoirs but have also revealed new complexities. Digital rock physics, which integrates high-resolution μCT imaging with pore-network modeling and numerical upscaling, now provides quantitative links between pore geometry and macroscopic rock properties such as permeability, velocity, and elastic moduli [10]. Similarly, modern seismic and geomechanical techniques such as full-waveform inversion and real-time microseismic monitoring are improving fracture detection and reservoir stress characterization [11]. Data-driven methods, particularly machine learning and data integration platforms, have also enabled rapid pattern recognition across multidisciplinary datasets, supporting facies classification, fracture prediction, and production forecasting [12]. However, translating these laboratory and digital insights into reliable field-scale models remains a major challenge [13].

Despite these advances, several uncertainties continue to constrain prediction and performance optimization in unconventional reservoirs.

Fluid transport in nanoporous media where adsorption, surface diffusion, and slippage dominate deviates from classical Darcy flow, complicating reserves estimation and production modeling [14]. Moreover, the scaling of fracture propagation and conductivity from micro-scale laboratory tests to field-scale stimulation remains poorly constrained [15]. Environmental and social concerns are equally pressing: hydraulic fracturing and wastewater disposal have been linked to induced seismicity in several regions [16], while water sourcing, treatment, and disposal create sustainability and cost challenges [17]. These issues have intensified the call for integrated geological, environmental, and economic frameworks to support responsible unconventional resource development.

The purpose of this review is to explore contemporary research in the petroleum geology of unconventional reservoirs and to outline directions for future investigation. The review consolidates geological fundamentals; source-rock characterization, thermal maturity, and basin-scale controls on hydrocarbon generation, and examines reservoir attributes such as mineralogical variability, nano- to macro-scale pore systems, and the role of natural fractures and stratigraphic architecture in compartmentalization. It also evaluates methodological advances in characterization and monitoring, including digital rock physics, laboratory petrophysics, and geophysical approaches such as seismic and microseismic analysis. Furthermore, it explores production mechanisms and geomechanical responses during stimulation and depletion and assesses environmental and socio-economic challenges such as water management, induced seismicity mitigation, and carbon intensity. By emphasizing multi-scale geological integration and highlighting case studies where geological insights have informed production optimization, the review aims to bridge the gap between academic research and industrial application. Ultimately, it seeks to identify key uncertainties, methodological gaps, and research opportunities that will enhance understanding and sustainable exploitation of unconventional petroleum systems in the context of the global energy transition.

Classification and Types of Unconventional Reservoirs

Unconventional reservoirs represent hydrocarbon accumulations that deviate from classical petroleum system behavior due to their low permeability, complex pore structures, and self-contained nature [18]. Unlike conventional traps, where hydrocarbons migrate from source to reservoir, unconventional systems generally retain hydrocarbons within their source or adjacent strata.

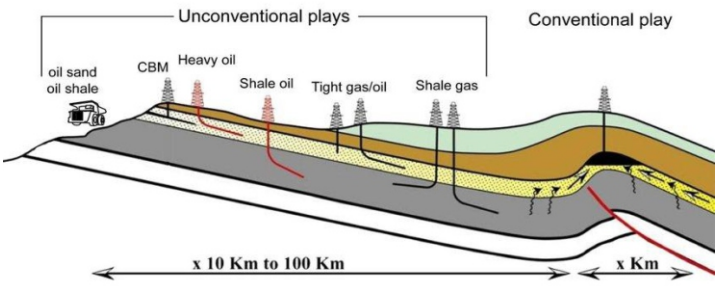

Figure 1. *Different types of unconventional plays. This diagram depicts the different types of unconventional hydrocarbon plays, including shale gas, tight gas, coalbed methane, tight oil, and oil sands.*
Sources: *[19]*

The Major categories of unconventional reservoirs are discussed below;

I. Shale (Tight) Oil and Gas Reservoirs

Shale and tight reservoirs are the most productive unconventional plays, serving simultaneously as source and reservoir rocks. Hydrocarbons occur within nano- to micro-scale pores and natural fractures, often requiring hydraulic fracturing and horizontal drilling to enhance flow. Productivity depends on total organic carbon (TOC), thermal maturity, brittleness, and fracture networks [20]. Mineral composition, especially the proportion of brittle quartz and carbonates relative to clays, governs stimulation efficiency [21]. Prominent examples include the Marcellus and Bakken (Figure 2), in North America and the Sichuan Basin in China [22].

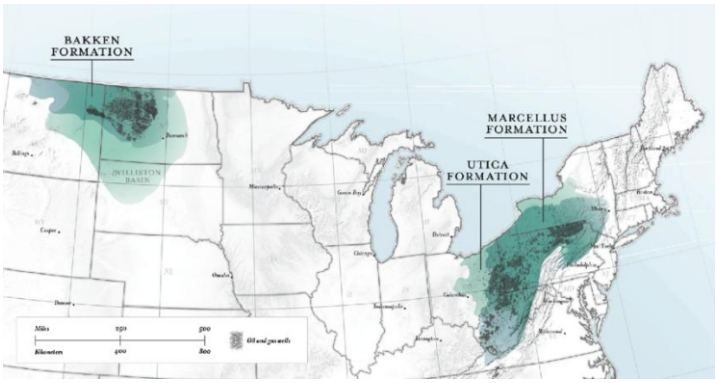

Figure 2. *Bakken, Marcellus, and Utica Shale Plays. This diagram depicts major unconventional shale plays Bakken, Marcellus, and Utica, highlighting key regions of hydrocarbon production in North America.*
Sources: *[23]*

ii. Tight Sandstone Reservoirs

Tight sandstones constitute another major unconventional resource type characterized by severely reduced porosity and permeability resulting from diagenetic compaction and cementation [24]. Unlike shale reservoirs, tight sandstones are typically sourced externally but share similar flow restrictions that necessitate artificial stimulation. Their pore systems are dominated by intergranular, intragranular, and dissolution pores connected through micro-fractures and nano-throats [25]. Reservoir quality is largely governed by depositional facies, burial history, and diagenetic evolution, particularly quartz overgrowth and clay cementation [26]. Geological case studies from the Ordos and Tarim basins demonstrate that understanding diagenetic sequences and fracture development is critical for predicting flow capacity and optimizing hydraulic fracturing design [27].

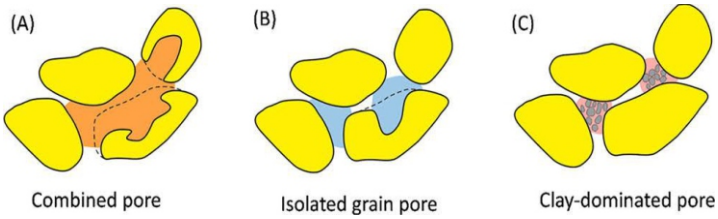

Figure 3. *Schematic diagram of the pore types of the tight sandstone: (A) combined pore, (B) isolated grain pore, and (C) clay-dominated pore.*
Source: *[28]*

iii. Coalbed Methane (CBM)

Coalbed methane resources represent a distinctive form of unconventional gas trapped within coal seams as adsorbed gas on internal surfaces and as free gas in cleats. Production primarily involves dewatering to reduce reservoir pressure and induce desorption [29]. The dual-porosity system of coal comprising low-permeability matrix blocks and higher-permeability cleat networks creates complex interactions between hydrology, geomechanics, and gas transport [30]. Geological factors such as coal rank, maceral composition, gas content, and stress regime control gas generation and deliverability [31]. Recent developments include CO_2-enhanced CBM recovery, which not only improves methane production but also serves as a viable carbon sequestration strategy [32]

iv. Heavy Oil, Oil Sands, and Gas Hydrates

Heavy oil and oil sands consist of viscous hydrocarbons generated through biodegradation and loss of lighter fractions. These reservoirs, often found in unconsolidated sands, require thermal recovery methods such as cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) to reduce viscosity and enable flow. The Athabasca and Cold Lake deposits of Canada remain the most significant global examples. Key geological factors include grain size, porosity, permeability, and overburden integrity, all of which influence steam efficiency and recovery rates [33].

Gas hydrates, by contrast, are crystalline compounds of water and gas, predominantly methane, formed in permafrost and deep marine sediments under high pressure and low temperature. These systems contain immense potential energy resources but present considerable challenges related to reservoir continuity, production stability, and environmental risk. Ongoing field experiments in the Nankai Trough (Japan) and South China Sea have achieved limited but significant gas production, offering new insights into hydrate-bearing sediment behavior [34].

Table 1. Comparative characteristics of major unconventional reservoir types

Reservoir Type	Host Rock	Hydrocarbon Phase	Porosity Range (%)	Permeability (mD)	Main Storage Mechanism	Typical Recovery Technique
Shale/Tight Oil & Gas	Organic-rich mudrock	Oil/Gas	2–8	<0.1	Adsorbed & free gas in nano-pores	Hydraulic fracturing, horizontal drilling
Tight Sandstone	Cemented sandstone	Oil/Gas	5–12	0.01–1	Intergranular & fracture pores	Multi-stage fracturing
Coalbed Methane	Coal seams	Gas	<5	0.001–1	Adsorbed gas on coal matrix	Dewatering, CO_2 injection
Heavy Oil/Oil Sands	Unconsolidated sand	Oil	25–35	1–5	Pore-filling viscous bitumen	Thermal (SAGD, CSS)
Gas Hydrate	Marine/permafrost sediments	Gas (CH_4)	Variable	Variable	Hydrate lattice	Depressurization, thermal stimulation

Source: [35]

Geological Framework of Unconventional Reservoirs

Understanding the geological framework of unconventional reservoirs is critical because the interplay of source rock generation, reservoir characteristics, stratigraphic-structural settings, and geomechanical behaviour controls hydrocarbon storage and producibility in low-permeability systems [35]. Unlike conventional reservoirs, where migration and accumulation dominate, unconventional systems require integration of generation, retention, and mechanical response within the same rock volume. The key geological parameters influencing unconventional reservoir quality are summarized in **Table 2**, which outlines their geological significance, typical ranges, and impact on hydrocarbon generation, storage, and production [36]. This section reviews current knowledge on source rock characteristics, reservoir rock properties, structural and stratigraphic controls, and geomechanical factors in unconventional plays.

Table 2. Key geological parameters controlling unconventional reservoir quality

Parameter	Geological meaning	Typical range/example	Impact on reservoir performance	References
TOC (%)	Organic richness of source rock	2–15 %	Controls hydrocarbon generation/storage	[37]
Ro (%)	Thermal maturity	0.6–2.5	Determines oil vs gas phase	[38]
Mineralogy	Quartz, carbonates, clays	Variable	Influences brittleness/fracturability	[39]
Porosity (%)	Storage capacity	2–10 %	Affects gas-in-place	[40]
Permeability (mD)	Flow capacity	<0.001–1	Governs deliverability	[41]

Source Rock Characteristics

Unconventional reservoirs originate in organic-rich source rocks that act both as hydrocarbon generators and storage media. Their effectiveness depends on total organic carbon (TOC), kerogen type, and thermal maturity [42]. **Figure 4**, illustrates this relationship for the Montney Formation, where TOC plotted against vitrinite reflectance (R_0) defines immature to dry-gas generation windows [43]. Montney samples show moderate to high TOC and R_0 values of ~0.6–2.0%, indicating mature to overmature conditions and confirming the formation's dual role as source and reservoir. Variations in organic matter distribution and micro-porosity strongly influence hydrocarbon storage and flow [44], while limited migration blurs the distinction between source, reservoir, and seal.

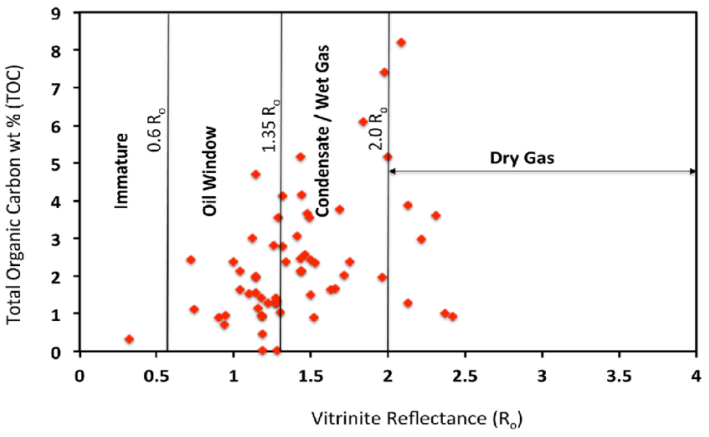

Figure 4. *Total Organic carbon (TOC) vs. vitrinite reflectance (Ro) showing the thermal maturity of Montney formation source-rock, and hydrocarbon generating phases in the Montney formation sediments from the study area, northeastern British Columbia*
Source: *[45]*

Reservoir Rock Properties

Reservoir efficacy in unconventional plays depends on matrix and fracture attributes, nano- to micro-scale pore systems, mineralogy and petrophysical heterogeneity. Pore size distributions in tight sandstones and shales frequently extend into the nano-scale, significantly reducing permeability and requiring stimulation to connect storage volume to flow pathways [46]. Mineralogical composition (clay content, quartz, carbonates) dictates brittleness and impacts fracture propagation [47]. A recent investigation in the Junggar Basin evaluated deep tight hybrid sedimentary rocks and demonstrated that mechanical parameters such as Young's modulus, Poisson's ratio, and brittleness index vary with mineral composition and confining pressure, directly impacting fracturing performance [48]. This relationship is clearly illustrated in Table 5, where variations in elastic and brittle properties reflect compositional heterogeneity and stress conditions. Hence, successful unconventional reservoir evaluation must incorporate detailed petrophysical, mineralogical, and mechanical characterisation.

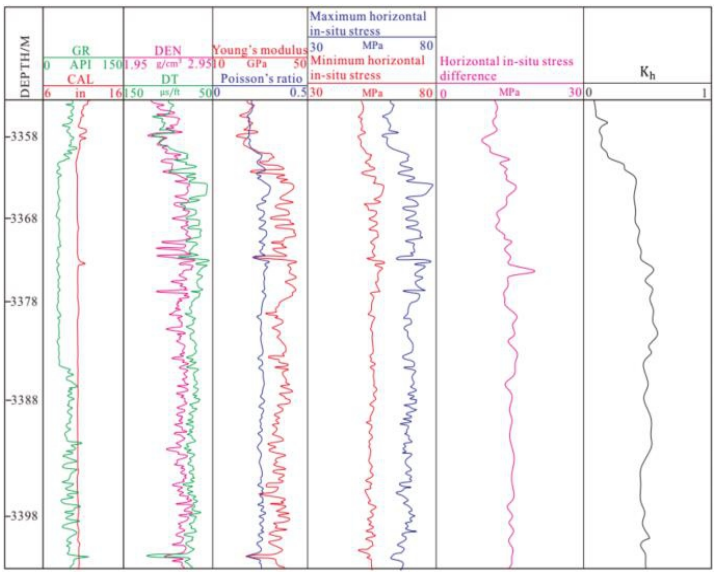

Figure 5. *Rock mechanics parameters and in-situ stress profile of J137 well.*

The diagram illustrates that Young's modulus increases while Poisson's ratio and horizontal stress difference vary with depth, reflecting lithological heterogeneity and confining pressure effects. A mechanically strong interlayer (3363–3378 m) exhibits elevated modulus and stress values, potentially acting as a fracture barrier.
Source: *[1]*

Structural and Stratigraphic Controls

The depositional environment, basin architecture, tectonic history, and stratigraphic context strongly influence unconventional reservoir quality and compartmentalisation. Basin-scale architecture determines burial, stress history and thermal evolution of source rocks; for example, coal-measure tight sand systems in China's basins show direct coupling between coal source fabrics and adjacent tight sandstone reservoirs [2]. Natural fractures formed during tectonic deformation or overpressure release serve as critical flow paths in low-permeability systems and also influence hydraulic fracturing outcomes. Stratigraphic heterogeneity, such as thin layering, variable lithofacies, and diagenetic overprints, can restrict lateral connectivity and create micro-compartmentalisation in unconventional reservoirs, thereby reducing effective drainage radii [3].

Geomechanical Properties and Fracture Behaviour

Geomechanics plays a central role in unconventional reservoir development because stimulation, production, and long-term reservoir behaviour are heavily influenced by rock mechanics. In low-permeability reservoirs, hydraulic fracturing aims to open new flow paths by overcoming mechanical resistance and promoting fracture propagation [4]. A recent editorial noted that geomechanics now permeates all phases of unconventional development from wellbore placement, through hydraulic stimulation, to depletion management and induced-seismicity monitoring [5]. Mechanical parameters such as brittleness index, stress field orientation, in-situ stress difference, and fracture toughness dictate the efficiency of fracture networks and hence recovery. For instance, quantitative evaluation of deep tight sandstone reservoirs in the Junggar Basin revealed that higher brittleness and larger principal stress difference improve fracturing performance [6]. Effective modelling thus integrates rock mechanical testing, geological fabric characterization, and field-scale monitoring of stimulation outcomes. The key structural and geomechanical factors influencing unconventional reservoir stimulation are summarized in Table 3.

Table 3. Structural and geomechanical factors affecting unconventional reservoir stimulation

Factors	Description	Influence on production	References
In-situ stress orientation	Directional stress field (σHmax, σHmin)	Governs fracture direction and propagation	[7]
Natural fracture density	Pre-existing joints/fractures	Enhances or diverts induced fractures	[8]
Brittleness Index	Derived from mineral composition	Higher brittleness = better fracture propagation	[9]
Layer stiffness contrast	Variation between beds	Limits vertical fracture growth	[10]
Depth and overburden stress	Burial effect	Higher stress increases breakdown pressure	[11]

Exploration and Characterization Techniques

In the domain of unconventional reservoir development, accurate exploration and characterization techniques are fundamental to identifying viable zones, reducing uncertainty, and optimizing production. Given the ultra-low permeability and complex pore networks of such plays, conventional exploration workflows are often insufficient. Instead, a multi-disciplinary approach integrating geological, geochemical, geophysical and petrophysical methods is required to delineate sweet spots, quantify reservoir properties, and evaluate producibility. This section reviews current practices in geological/geochemical methods, geophysical techniques, and petrophysical and reservoir-evaluation workflows as applied to unconventional systems.

Geological and Geochemical Methods

Geological and geochemical characterisation provides the foundation for unconventional reservoir evaluation by assessing source-rock quality, thermal maturity, organic content, mineralogy, and depositional facies. For example, integrated well-log and geochemical analyses enable determination of TOC, kerogen type, and maturity in shale and tight reservoirs [12]. At the same time, experimental and simulation studies have quantified the significance of micro-structural organic pore networks in deep unconventional reservoirs [13]. Facies mapping, core description, and basin modelling remain essential to understanding the spatial variability of reservoir and source rocks and to identifying sweet-spot zones. Additionally, as illustrated in Figure 6 by the downhole microseismic geophone array used to record fracturing-induced seismic events [14]. geophysical observations can complement geological and geochemical data by constraining fracture geometry and stress orientation within heterogeneous formations.

Geophysical Methods

Geophysical techniques in unconventional reservoirs have evolved beyond structural imaging to quantitative reservoir characterisation. Advanced seismic inversion, rock-physics modelling, and elastic property analysis allow estimation of parameters such as microfracture porosity and gas saturation in tight sandstones [15]. Moreover, emerging workflows incorporating distributed acoustic sensing (DAS), microseismic monitoring, and full-waveform inversion deliver enhanced fracture mapping and geomechanical insight [16]. The principle of microseismic monitoring illustrated in Figure 6, demonstrates how integrated geophysical, petrophysical, and geological data enable more precise lateral and vertical targeting in unconventional plays.

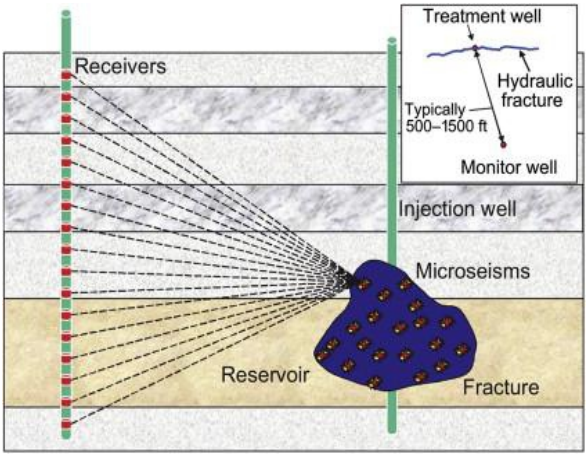

Figure 6. *Microseismic downhole geophone array receiving seismic events. This diagram illustrates a microseismic downhole geophone array used to detect and record seismic events during hydraulic fracturing operations.*
Source: *[17]*

Petrophysical and Reservoir Evaluation

Petrophysical and reservoir-evaluation workflows for unconventional reservoirs require specialised techniques to handle nano-scale pores, adsorption phenomena, and heterogeneous stimulation responses. For instance, [18] demonstrated a comprehensive petrophysical workflow combining core, log and dynamic data in a tight sandstone play in West Africa, improving permeability prediction and reducing uncertainty. In addition, integrated petrophysical and geostatistical methods enhance reservoir modelling by capturing spatial variability and uncertainty in reservoir properties [19]. These workflows support sweet-spot identification, well placement, and stimulation design in unconventional systems, as exemplified in the deterministic shale gas petrophysical workflow illustrated in Figure 7.

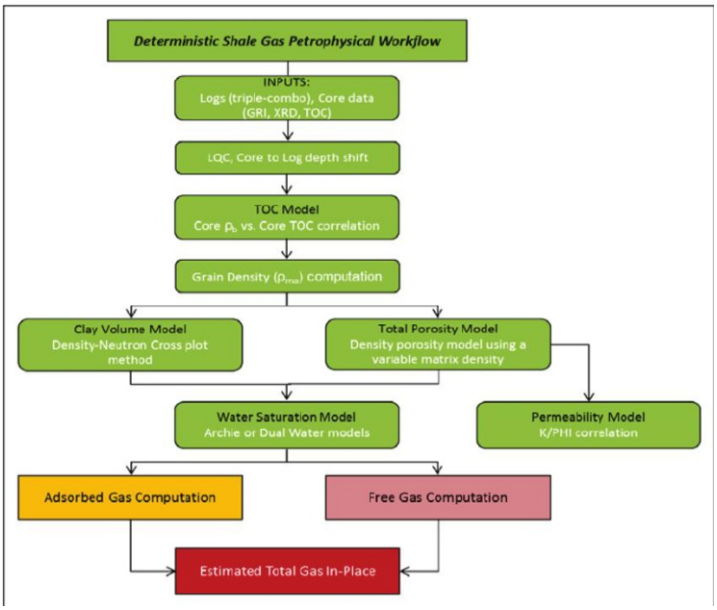

Figure 7. *Deterministic workflow in unconventional reservoir quality evaluation. This diagram illustrates a deterministic workflow for unconventional reservoir quality evaluation based on petrophysical analysis.*
Source: *[20]*

Technological Innovations in Unconventional Reservoir Development

Modern unconventional reservoirs demand cutting-edge technologies to overcome their inherent geological, petrophysical, and operational challenges. Innovations span from nano-scale imaging and digital rock physics to enhanced recovery methods and real-time monitoring systems. These advances, however, also expose gaps in understanding and application that define the agenda for future research.

Advances in Characterization Techniques

The integration of micro-CT imaging, digital rock physics, and multiscale rock-physics modelling has significantly improved our insight into pore-scale structure and behaviour in low-permeability media [21].

Meanwhile, refined rock-physics models that link velocity, porosity, and mineralogy facilitate log interpretation in unconventional settings [22]. Combined with machine-learning algorithms applied to petrophysical and seismic datasets, these approaches support more accurate facies prediction and reservoir quality assessment [23].

Enhanced Recovery and Field Deployment Techniques

Emerging production improvement methods are expanding beyond traditional multistage fracturing to include processes such as CO_2 huff-and-puff in shale and tight formations. In one study, CO_2 huff-and-puff was shown to enhance oil recovery in a shale volatile oil formation when modelled with molecular diffusion and stress sensitivity. Another investigation used online NMR to optimise CO_2 injection parameters in shale reservoirs, highlighting the importance of well timing and soak periods [24]. These methods underline how advances in both technology and workflow design can directly improve recovery in unconventional systems.

Integration, Digital Twins and Real-Time Monitoring

Real-time monitoring, distributed sensing, and digital-twin frameworks are now advancing from concept to deployment in the oil and gas industry. For example, applications of digital-twin technology in gas systems demonstrate the potential for integrated sensor data, workflow automation and virtual-replica modelling [25]. Yet, the adoption of these technologies in unconventional reservoirs remains nascent, with challenges around data integration, model fidelity and operational decision-making.

Production Mechanisms and Reservoir Behavior

Production from unconventional reservoirs is fundamentally different from conventional systems: low permeability, complex pore geometries, and limited natural connectivity mean that fluid flow, stimulation response and reservoir behaviour must be understood through mechanisms rather than simple Darcy flow [26]. In this section, we examine key production mechanisms in unconventional systems, including nano-scale diffusion and adsorption, induced and natural fracturing, and enhanced recovery approaches and explore how reservoir behavior (decline profiles, heterogeneity, stimulation response) is shaped by these mechanisms.

Multi-mechanistic Flow in Nano-porous and Fractured Media

Unconventional reservoirs often require more than classical Darcy flow: in nano-pores and kerogen-hosted porosity, adsorption/desorption, surface diffusion, and molecular flow become significant alongside viscous flow in fractures [27]. A log-log study of tight gas reservoirs showed that the transition between viscous and diffusion-dominated regimes depends on pore-throat size and connectivity [28]. Natural fractures and induced hydraulic fractures provide high-conductivity pathways, but the matrix remains the major storage domain. The coupling of fracture–matrix flow is therefore critical for production modeling and forecasting.

Table 4. Dominant flow mechanisms and governing parameters in unconventional Reservoirs

Mechanisms	Governing parameter(s)	Typical scales	Influence on production
Viscous (Darcy) Flow	Permeability, pressure gradient	µm–mm	Dominates in fractures
Knudsen Diffusion	Mean free path, pore radius	nm	Controls nano-pore transport
Surface Diffusion	Adsorption energy, surface area	nm	Enhances gas mobility
Desorption	Pressure, temperature	nm–µm	Releases adsorbed gas
Fracture–Matrix Exchange	Capillary pressure, fracture spacing	cm–m	Key to sustained flow

Adaptee from [29]

Stimulated Reservoirs, Fracture Networks and Heterogeneity

The production performance of unconventional wells depends heavily on the geometry and connectivity of induced fracture networks and how these interact with natural fractures and stratigraphic heterogeneity. The injection of fracturing fluids and proppants creates enhanced paths, but their behaviour is controlled by rock mechanics, bedding planes, stress anisotropy and natural fracture density [30]. Reservoir heterogeneity including variations in mineralogy, pore-system architecture and mechanical properties, limits effective drainage and contributes to rapid production declines. Understanding the spatial heterogeneity of fracture conductivity and reservoir compartments is essential for optimizing recovery.

Production Decline Behavior and Enhanced Recovery Techniques

Unconventional reservoir wells commonly exhibit very high initial production rates followed by steep declines due to depletion of stimulated volumes, loss of conductivity and limited connectivity. Recent review work shows that decline-curve behaviour in multi-fractured horizontal wells can be improved by enhanced recovery techniques such as gas injection, CO_2 huff-and-puff or waterless fracturing to mobilise hydrocarbons in low-connectivity zones [31]. Additionally, the coupling of production mechanisms and reservoir behaviour underscores the need for integrated monitoring, adaptive completion strategies and longer-term modelling of reservoir performance.

Table 4. Enhanced recovery methods and mechanistic impacts of unconventional reservoirs

Method	Working Mechanism	Key Benefits	Challenges	Reference
CO_2 Huff-and-Puff	Injection → soak (adsorption/pressure drive) → production	Improves oil mobility, can provide pressure support and partial miscibility	Requires CO_2 supply; sequestration risk; operational cost	[32]
Gas injection (N_2, flue gas)	Pressure support; gas drive	Readily available gases; pressure maintenance	Limited miscibility; potential sweep inefficiency	[33]
Waterless fracturing (LPG/CO_2 foam, nitrogen)	Uses non-aqueous fluids/gases to create fractures	Reduces water handling; potential less formation damage	Operational complexity; safety and handling of gases/liquids	[34, 35]
Smart completion & re-fracs	Targeted re-stimulation of poorly drained fractures	Restores conductivity, extends well life	Costly; effectiveness depends on initial frac geometry	[36, 37]

Environmental and Economic Considerations

The development of unconventional reservoirs presents both economic opportunities and significant environmental challenges. While these resources can contribute substantially to energy supply and local employment, their extraction often involves high capital investment, water usage, induced seismicity and greenhouse-gas emissions [38]. A comprehensive assessment of unconventional petroleum systems must therefore balance economic viability, regulatory frameworks and environmental stewardship. This section reviews economic drivers and constraints, key environmental impacts and mitigation strategies, and the role of regulation and community engagement [39].

Economic Drivers and Constraints

Unconventional reservoir development is characterised by high upfront capital expenditure (CAPEX) due to extended drilling, multistage hydraulic fracturing and complex completions [40]. Profitability depends on oil/gas price, well placement, recovery factor and decline rate. Market volatility and logistical constraints (e.g., water disposal, infrastructure) further limit economic viability. For example, energy economics assessments document how public costs and externalities influence development incentives in shale gas regions [41]. Industry models show that reducing non-productive time and improving drilling/completion efficiency are key levers for turning unconventional plays into economically viable assets.

Environmental Impacts and Mitigation

The extraction of hydrocarbons from unconventional reservoirs can entail substantial environmental risks: high-volume water use and flowback water management, potential aquifer contamination, induced seismicity, land-use disturbance and fugitive methane emissions [42]. Despite these risks, some life-cycle assessments find that natural-gas production from shale may yield lower air-pollution impacts than coal when produced with best practices [43]. Mitigation strategies focus on water reuse, closed-loop fluid management, microseismic monitoring, methane capture systems and regulatory oversight to minimise ecological footprint and public health risks.

Regulation, Social License and Sustainability

Regulatory frameworks and gaining the social licence to operate are becoming pivotal for unconventional hydrocarbon projects. Community acceptance hinges on transparent risk communication, baseline environmental monitoring, fair benefit sharing and long-term site reclamation planning. Economic assessments highlight that households near shale-gas development incur "averting" expenditures in response to perceived contamination risks, signalling community cost burdens [44]. In parallel, governance mechanisms are evolving to align with net-zero commitments and circular economy principles in unconventional energy development [45]. Integrated governance combining geology, economics, and social science is essential to ensure that unconventional reservoir development can proceed sustainably in the energy transition.

Figure 5. Key Environmental and Economic Dimensions of Unconventional Reservoir Development

Dimensions	Key Issues	Recent insight	Reference
Water Use	High fracturing water demand (10–25 ML per well); disposal and contamination risks	Up to 70 % of flowback water can be recycled, reducing environmental footprint	[46]
Methane & GHG Emissions	Fugitive methane and CO_2 from operations	Leak detection and repair programs cut methane losses by > 50 %	[47, 48]
Induced Seismicity	Linked mainly to wastewater injection	Seismic monitoring and volume control mitigate events > M 3.0	[1]
Land & Ecosystem Impact	Pad construction and fragmentation of habitats	Multi-well pads and directional drilling minimize surface footprint	[2]
Economic Viability	Breakeven price = US $45–70 bbl; EROI ≈ 4–7	Efficiency gains via longer laterals and digital optimization	[3]

Future Research Priorities

Looking ahead, research must increasingly emphasize cross-disciplinary integration that unites geological, engineering, and environmental datasets. Future frameworks should embed carbon management, circular water use, and ecosystem sustainability within the core of reservoir evaluation and management. Advances in AI-driven decision systems, sensor networks, and real-time geochemical monitoring offer the potential to enhance both economic efficiency and environmental performance. By aligning technological innovation with sustainability objectives, the petroleum industry can ensure that unconventional resource development remains viable and responsible within the context of the global energy transition.

The future of unconventional resource development depends on harmonizing environmental stewardship with economic optimization. Research priorities should include methane capture technologies, carbon-neutral production systems, and comprehensive lifecycle assessments. Integrating environmental accounting frameworks into field development planning will ensure that cost analyses adequately reflect emissions and ecosystem impacts [4].

Collaboration among policymakers, operators, and researchers is essential to establish sustainability benchmarks that enable unconventional resource exploitation to contribute constructively to global decarbonization efforts rather than detract from them.

Conclusion

Unconventional petroleum reservoirs have revolutionized hydrocarbon exploration by revealing vast resources in geologically complex, low-permeability formations. Advances in reservoir characterization, digital modeling, and geomechanical analysis have improved understanding of hydrocarbon generation, storage, and flow behavior. Despite these gains, major challenges remain in predicting fluid dynamics, optimizing recovery, and minimizing environmental impacts. The sustainability of unconventional resource development depends on balancing technological innovation with environmental responsibility and economic efficiency. Future progress will rely on integrated, cross-disciplinary approaches that link geological insight with data-driven technologies. By aligning exploration strategies with sustainable practices, petroleum geology can continue to evolve, supporting both

energy security and the global transition toward cleaner energy systems.

Acknowledgement
We thank all the researchers who contributed to the success of this research work.

Conflict of Interest
The authors declared that there are no conflicts of interest.

Funding
No funding was received for this research work.

References

1. Alvarez, R. A., *et al.* (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. Science. 361(6398); 186–188. https://doi.org/10.1126/science.aar7204
2. Bader, M., Clapp, R. G., Nihei, K. T. and Biondi, B. (2023). Moment-tensor inversion of perforation shots using distributed acoustic sensing. arXiv. https://arxiv.org/abs/2303.07260
3. Bera, A., Kumar, S., Foroozesh, J. and Gharavi, A. (2022). Multiphysics gas transport in nanoporous unconventional reservoirs: Challenges of mathematical modelling. Journal of Natural Gas Science and Engineering. 103; 104649. https://doi.org/10.1016/j.jngse.2022.104649
4. Brittingham, M. C., Maloney, K. O., Farag, A. M., Harper, D. D. and Bowen, Z. H. (2014). Ecological risks of shale oil and gas development to wildlife, aquatic resources and their habitats. Environmental science & technology. 48(19); 11034–11047. https://doi.org/10.1021/es5020482
5. Bui, B. T. (2023). Geomechanics in unconventional resource development. ArXiv. https://arxiv.org/abs/2305.17642
6. Burnett, J. M. (2015). Foreword: Unconventional oil and gas development: Economic, environmental, and policy analysis. Agricultural and Resource Economics Review. 44(2):iii-xvii. DOI:10.1017/S1068280500010182
7. Cai, J., Zhao, L., Zhang, F. and Wei, W. (2022). Advances in multiscale rock physics for unconventional reservoirs. Advances in Geo-Energy Research. 6(4); 271–275.
8. Clarkson, C. R. and Qanbari, F. (2016). A semi-analytical method for forecasting wells completed in low-permeability, undersaturated CBM reservoirs. Journal of Natural Gas Science and Engineering. 30; 19–27. https://doi.org/10.1016/j.jngse.2016.01.040
9. Dvorkin, J., Walls, J. and Davalos, G. (2021). Velocity–porosity–mineralogy model for unconventional shale and its applications to digital rock physics. Frontiers in Earth Science. 8; 613716. https://doi.org/10.3389/feart.2020.613716
10. Eaton, D. W. (2022). Seismicity induced by the development of unconventional oil and gas resources. In J. Stolz, D. Bain, & M. Griffin (Eds.), Environmental impacts from the development of unconventional oil and gas reserves. Cambridge University Press. 173–213. https://doi.org/10.1017/9781108774178.011
11. Egbobawaye, E. I. (2017). Petroleum Source-Rock Evaluation and Hydrocarbon Potential in Montney Formation Unconventional Reservoir, Northeastern British Columbia, Canada. Natural Resources. 08(11):716-756. DOI:10.4236/nr.2017.811045
12. Ellsworth, W. L. (2013). Injection-induced earthquakes. Science. 341(6142); 1225942. https://doi.org/10.1126/science.1225942
13. Esiri, A. E., Jambol, D. D. and Ozowe, C. (2024). Enhancing reservoir characterization with integrated petrophysical analysis and geostatistical methods. Research Journal of Multidisciplinary Studies. 7(2); 168–179. https://doi.org/10.53022/oarjms.2024.7.2.0038
14. Euzen, T. (2011). Shale Gas: An Overview. DOI:10.13140/RG.2.1.2236.6242
15. Fang, X., Wang, Y., Zhang, Y. et al. (2025). Rock mechanical properties and fracability evaluation of deep tight hybrid sedimentary rocks reservoirs-a case study of Lucaogou formation in Jimsar Sag, Junggar Basin. J Petrol Explor Prod Technol. 15; 67. https://doi.org/10.1007/s13202-025-01960-6
16. Gao, Y., Liu, N., Li, Z., Cheng, L. and Sun, J. (2024). Optimization of CO_2 injection huff-and-puff process in shale reservoirs based on NMR technology. Applied Sciences. 14(6); 2411. https://doi.org/10.3390/app14062411
17. Gharavi, A., Abbas, K. A., Hassan, M. G., Haddad, M., Ghoochaninejad, H., Alasmar, R., Al-Saegh, S., Yousefi, P. and Shigidi, I. (2023). Unconventional reservoir characterization and formation evaluation: A case study of a tight sandstone reservoir in West Africa. Energies. 16(22); 7572. https://doi.org/10.3390/en16227572
18. Guo, C., Wei, M. and Liu, H. (2015). Modeling of gas production from shale reservoirs considering multiple transport mechanisms. PLOS ONE. 10(12); e0143649. https://doi.org/10.1371/journal.pone.0143649
19. Guo, C., Wei, M. and Liu, H. (2015) Modeling of Gas Production from Shale Reservoirs Considering Multiple Transport Mechanisms. PLoS ONE. 10(12): e0143649. doi:10.1371/journal.pone.0143649
20. He, F., Huang, X., Yang, Y., Bu, C., Xing, H. and Zhang, S. (2024). Review on critical liquid-loading models and their application in deep unconventional gas reservoirs. Frontiers in Energy Research. 12; 1407384. https://doi.org/10.3389/fenrg.2024.1407384
21. Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H. and Pétron, G. (2014). The environmental costs and benefits of fracking. Annual Review of Environment and Resources. 39; 327-362. https://doi.org/10.1146/annurev-environ-031113-144051
22. Jarvie, D. M. (2011). Unconventional oil petroleum systems: shales and shalehybrids. Search and DiscoveryArticle #80131. 1–21.
23. Junod, A. N. and Jacquet, B. J. (2019). Shale gas in coal country: Testing the Goldilocks Zone of energy impacts in the western Appalachian range. Energy Research & Social Science. 55(1):155-167. DOI:10.1016/j.erss.2019.04.017
24. Kondash, A. J. and Vengosh, A. (2015). Water footprint of hydraulic fracturing. Environmental Science & Technology Letters. 2(10); 276–280. https://doi.org/10.1021/acs.estlett.5b00211
25. Li, W., Hu, D., Chang, Y., Li, Y., Guo, G., Shi, Q. and Zhang, Z. (2024). Diagenetic controls over reservoir quality of tight sandstone in the lower Jurassic reservoir in the Lenghu area, the north margin of Qaidam basin. Front. Earth Sci. https://doi.org/10.3389/feart.2024.1298802
26. Liu, J., Ding, W., Liu, S., Liu, K. and Liu, D. (2023). Editorial: Unconventional reservoir geomechanics. Frontiers in Earth Science. 11; 1126288. https://doi.org/10.3389/feart.2023.1126288
27. Meyer, R. F., Attanasi, E. D. and Freeman, P. A. (2007). Heavy oil and natural bitumen resources in geological basins of the world (U.S. Geological Survey Open-File Report 2007–1084, v. 1.0). U.S. Geological Survey. https://pubs.usgs.gov/of/2007/1084/
28. Moore, T. (2012). Coalbed methane: A review. International Journal of Coal Geology. 101:36–81. DOI:10.1016/j.coal.2012.05.011
29. Pang, X. (2023). Introduction to Quantitative Evaluation of the Whole Petroleum System. In book: Quantitative Evaluation of the Whole Petroleum System. 1-48. DOI:10.1007/978-981-99-0325-2_1

30. Perry, S. L. (2012). Environmental Reviews and Case Studies: Addressing the Societal Costs of Unconventional Oil and Gas Exploration and Production: A Framework for Evaluating Short-Term, Future, and Cumulative Risks and Uncertainties of Hydrofracking. Environmental Practice. 14(4); 352–365. https://doi.org/10.1017/S1466046612000336
31. Qi, Q., Dai, L., Lebedev, M., Müller, T. and Zhang, J. (2023). Editorial: Rock physics modelling and well-log practice for unconventional reservoirs. Frontiers in Earth Science. 11; 1234699. https://doi.org/10.3389/feart.2023.1234699.
32. Qin, L., Zhang, X., Deng, X. and Cao, L. (2020). Effect of Natural Fractures on Shale Gas Reservoir Reconstruction. IOP Conference Series Materials Science and Engineering. 780(4):042046. DOI:10.1088/1757-899X/780/4/042046
33. Qiu, L., Wang, S., Hu, B., Yan, J., Deng, S., Shen, J., Shi, C., Ge, X. and Chen, B. (2024). A review on high-value development and utilization of unconventional methane-containing gaseous fuel resources. Energy Conversion and Management. 311; 118980. https://doi.org/10.1016/j.enconman.2024.118980
34. Rodvelt, G. (2014). Chapter 6 - Vertical Well Construction and Hydraulic Fracturing for CBM Completions. Coal Bed Methane, Elsevier. 101-135. https://doi.org/10.1016/B978-0-12-800880-5.00006-1.
35. Sun, T., Merletti, G., Patel, H. and Cadwallader, S. (2015). URTeC: 2152246 Advanced Petrophysical, Geological, Geophysical and Geomechanical Reservoir Characterization - Key to the Successful Implementation of a Geo-Engineered Completion Optimization Program in the Eagle Ford Shale. DOI:10.15530/urtec-2015-2152246
36. Wang, W., Li, W. and Xu, S. (2022).Classifications of the Reservoir Space of Tight Sandstone Based on Pore Structure, Connectivity, and Fractal Character: A Case Study from the Chang 7 Member of the Triassic Yanchang Formation in the Ordos Basin, China. ACS Omega. 7(12); 10627–10637. https://doi.org/10.1021/acsomega.2c00252
37. Wei, J., Fang, Y., Lu, H. and Lu, H. (2018). Distribution and characteristics of natural gas hydrates in the Shenhu Sea Area, South China Sea. Marine and Petroleum Geology. 98. DOI:10.1016/j.marpetgeo.2018.07.028
38. Wibowo, R. C., Putri, A. C. E. and Dewanto, O. (2023). Analysis of unconventional oil and gas reservoirs using well logging, geochemical and seismic data. Jurnal GeoCelebes. 7(2); 154-167. https://doi.org/10.20956/geocelebes.v7i2.20603
39. Wrenn, D. H., Klaiber, H. A. and Jaenicke, E. C. (2016). Unconventional shale gas development, risk perceptions, and averting behavior: Evidence from bottled water purchases. Journal of the Association of Environmental and Resource Economists. 3(4); 779-817. https://doi.org/10.1086/688487
40. Wu, W., Lu, D. and Elsworth, D. (2022). Fluid injection-induced fault slip during unconventional energy development: A review. Energy Reviews. 1; 100007.
41. Yan, L. and Song, Y. (2024). Physical and experimental simulation of unconventional reservoir formation for Carboniferous in the Hudson oilfield, Tarim Basin, China. Frontiers in Earth Science. 12; 1430019. https://doi.org/10.3389/feart.2024.1430019
42. Yun, J., Kim, S. and Kim, J. (2024). Digital twin technology in the gas industry: A comparative simulation study. Sustainability. 16(14); 5864. https://doi.org/10.3390/su16145864
43. Zhang, D., Zhang, T., He, S., Zhu. C. and Gong, L. (2025). CO2-Enhanced oil recovery in unconventional reservoirs: Motivation, mechanisms, factors, challenges and methods. Computational Energy Science. 2(1): 4-9. https://doi.org/10.46690/compes.2025.01.02
44. Zhang, X. (2023). Shale gas transport model considering gas adsorption and desorption. International Journal of Energy. 2(2):51-55. DOI:10.54097/ije.v2i2.7768
45. Zhao, F., Yang, C., Huang, S., Yang, M., Sun, H. and Chen, X. (2024). Experimental investigation of CO_2 huff-and-puff enhanced oil recovery in fractured low-permeability reservoirs: Core-scale to pore-scale. Energies. 17(23); 6207. https://doi.org/10.3390/en17236207
46. Zhao, W. and Su, X. and Xia, D. and Hou, S. and Wang, Q. and Zhou, Y. (2022). "Enhanced coalbed methane recovery by the modification of coal reservoir under the supercritical CO2 extraction and anaerobic digestion," Energy, Elsevier. 259(C). DOI: 10.1016/j.energy.2022.124914
47. Zou, C. (2017). Unconventional petroleum geology (2nd ed.). Earth and planetary sciences. https://shop.elsevier.com/books/unconventional-petroleum-geology/zou/978-0-12-812234-1
48. Zou, C. N. (2013). Unconventional Petroleum Geology. DOI:10.1016/C2011-0-06250-6