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Perspective

Formation mechanisms of high-quality ultra-deep clastic reservoirs: Progress, scientific challenges and future directions

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Abstract:
As hydrocarbon exploration continues to advance into ultra-deep formations, conventional theories of reservoir formation based primarily on compaction, pore preservation, and dissolution are increasingly being challenged. Growing exploration practice indicates that the formation of high-quality ultra-deep clastic reservoirs cannot be explained simply as a deeper continuation of conventional deep reservoir evolution. Instead, ultra-deep reservoirs may represent a distinct geological regime, where reservoir evolution is governed by physical and chemical principles fundamentally different from those operating under conventional burial conditions. This work reviews the evolution of scientific understanding of reservoir formation in deep and ultra-deep clastic reservoirs and identifies several fundamental scientific issues that remain unresolved. It is suggested that the formation of high-quality ultra-deep reservoirs should be interpreted as the evolution of an open reservoir-forming system driven by the coupled interactions among the mass, thermal, pressure, stress, fluid, and chemical fields. Accordingly, the research paradigm is shifting from pore evolution toward the reservoir-forming system. More importantly, this paradigm shift may provide the conceptual foundation for an emerging discipline of Ultra-deep Reservoir Geology, offering a new theoretical framework for understanding, predicting, and evaluating high-quality reservoirs in the ultra-deep subsurface.

1. Introduction

Deep and ultra-deep hydrocarbon resources have become a strategic frontier for sustaining global oil and gas exploration. In China, reservoirs buried at depths of 4,500-6,000 m in onshore basins are generally classified as deep, whereas those deeper than 6,000 m are regarded as ultra-deep. In offshore settings, the corresponding depth ranges are 3,000-4,500 m for deep reservoirs and > 4,500 m for ultra-deep reservoirs. Over the past decade, a series of major exploration breakthroughs have been achieved in deep and ultra-deep formations. Effective reservoirs and commercially productive hydrocarbon accumulations have been discovered at burial depths exceeding 7,000 m, and even beyond 10,000 m, challenging the long-held assumption that progressive burial inevitably leads to reservoir destruction. These discoveries indicate that conventional models are no longer sufficient to explain the formation of high-quality ultra-deep reservoirs.

Over the past decades, extensive research has focused on porosity reduction by compaction (Carbillet et al., 2022),

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mechanisms of pore preservation (Li et al., 2025), and secondary porosity generation through dissolution (Weber et al., 2021), leading to a relatively well-established theoretical framework for deep clastic reservoirs. However, as exploration continues to advance into ultra-deep settings, a fundamental question has emerged: Do ultra-deep reservoirs simply represent a further stage of burial evolution, or do they constitute a distinct evolutionary regime governed by different geological processes? Addressing this question is essential not only for advancing our understanding of ultra-deep reservoir formation, but also for developing the next generation of theories for predicting high-quality reservoirs in the deep subsurface.

2. Evolution in understanding the formation of high-quality deep/ultra-deep reservoirs

The understanding of deep clastic reservoir evolution has progressed through three major conceptual stages: porosity loss, pore preservation, and pore modification. Early studies primarily focused on reservoir densification driven by mechanical compaction, pressure solution, and cementation, establishing the classical paradigm that progressive burial inevitably leads to continuous porosity reduction (Houseknecht, 1987). Since the 1970s, increasing attention has been directed toward mechanisms of pore preservation (Li et al., 2025), such as chlorite coatings, rigid grain frameworks, and fluid overpressure (Zhang et al., 2025), which were recognized as key factors in mitigating porosity loss during deep burial. From the 1980s, dissolution-driven secondary porosity became a major research focus, with fluid-rock interactions widely regarded as an important mechanism for reservoir quality enhancement (Schmidt and McDonald, 1979).

Since the beginning of the twenty-first century, it has become increasingly evident that none of these mechanisms alone can adequately explain the occurrence of high-quality ultra-deep reservoirs. Instead, reservoir evolution is now understood to be governed by the coupled effects of depositional architecture, diagenetic processes, tectonic deformation, and multi-sourced fluid activity (Bjørlykke, 2014). Consequently, research has gradually shifted from analyses of individual diagenetic processes toward an integrated, multi-process perspective that emphasizes the coupling among multiple geological controls.

3. Key scientific questions

Despite substantial advances over the past decades, several fundamental questions concerning the formation of high-quality ultra-deep clastic reservoirs remain unresolved.

First, do ultra-deep reservoirs represent a distinct stage of reservoir evolution? As burial depths increase into the ultra-deep domain, reservoirs are subjected to thermal, pressure, and stress conditions far beyond those encountered in conventional deep settings (Dou et al., 2026). Under such extreme conditions, the kinetics of mineral reactions, the physical properties of formation fluids, and the mechanical behavior of rocks may all depart fundamentally from those observed in conventional deep reservoirs (Niemeijer et al., 2002; Konrad-Schmolke et al., 2018). Consequently, reservoir evolution may no longer follow the same physical and chemical principles established for shallow and deep burial, but instead enter a distinct evolutionary regime governed by different controlling mechanisms. Whether ultra-deep reservoirs simply represent the continuation of progressive burial or a fundamentally different stage of reservoir evolution therefore remains one of the most important unresolved questions. If the latter is confirmed, ultra-deep reservoirs should be regarded not merely as a deeper exploration target, but as a new geological domain requiring its own theoretical framework, i.e., an emerging discipline that may be termed Ultra-deep Reservoir Geology.

Second, is the development of high-quality reservoirs controlled primarily by pore preservation or by subsequent reservoir modification? Both the preservation of primary porosity and post-burial fluid-driven modification have been recognized as critical controls on reservoir quality (Worden et al., 2018). However, their relative contributions and dynamic interactions throughout reservoir evolution have yet to be quantitatively constrained.

Third, does tectonic stress act predominantly as a destructive or a constructive force? Tectonic stress enhances compaction and pressure solution, but also promotes fracture development and fluid migration (Fall et al., 2015). Its dual role in reducing pore space while simultaneously improving reservoir effectiveness through fracture creation remains one of the major unresolved issues in ultra-deep reservoir research.

Fourth, has the role of deep-seated fluids been underestimated? Deep-sourced fluids, hydrothermal fluids, and fault-controlled fluid flow are increasingly recognized as important agents of reservoir modification (Haile et al., 2018). Their contributions to pore-throat reorganization, fracture development, and the improvement of reservoir effectiveness require further investigation.

Fifth, do hydrocarbon-water-rock reaction pathways fundamentally change under ultra-deep conditions? Under extreme temperatures and pressures, extensive thermal degradation of organic matter and hydrocarbons continuously modifies fluid composition and reactivity, leading to coupled hydrocarbon-water-gas-rock interactions that differ from those in conventional burial settings (Yuan et al., 2025). Whether these processes obey fundamentally different physicochemical principles and reaction pathways remains poorly understood and represents a key challenge for developing a new theoretical framework for ultra-deep reservoir evolution.

Finally, should future research shift its focus from pore evolution to reservoir effectiveness? In ultra-deep reservoirs, the presence of pore space alone is insufficient to determine reservoir quality. Instead, reservoir performance is controlled by the combined characteristics of pore systems, fracture networks, and fluid flow capacity (Pranter et al., 2006). Consequently, future studies should place greater emphasis on the evolution of reservoir effectiveness rather than porosity alone.

These questions are not independent but are hierarchically related. The first concerns whether ultra-deep reservoirs constitute a fundamentally new geological regime. The following four questions address the dominant geological processes governing reservoir evolution under such extreme conditions, whereas the final question concerns the appropriate conceptual framework for future research. Together, these questions define the key scientific challenges that must be addressed to establish a new theoretical understanding of ultra-deep reservoir formation.

4. From pore evolution to the reservoir-forming system: A new perspective on ultra-deep reservoir formation

Over the past decades, research on deep clastic reservoirs has largely focused on a single fundamental question: why do pores survive progressive burial? Whether emphasizing pore preservation or dissolution-induced secondary porosity, most existing models have been developed within the conceptual framework of pore evolution. However, as exploration extends into ultra-deep and even approximately 10 km-deep reservoirs, an increasing number of geological observations can no longer be adequately explained by pore evolution alone. It is suggested that the focus of ultra-deep reservoir research should shift from individual pores to the reservoir-forming system as the fundamental unit of investigation.

Within this framework, reservoirs should no longer be regarded as passive geological bodies that simply preserve or lose pore space during burial. Instead, they are best viewed as open and dynamic reservoir-forming systems that undergo continuous reorganization throughout their geological evolution. This evolution is governed by the coupled interactions among six fundamental fields: the mass field, thermal field, pressure field, stress field, fluid field, and chemical field. The mass field defines the initial lithological composition and reservoir architecture. The thermal field controls reaction kinetics and the progression of diagenesis. The pressure field regulates effective stress and fluid-pressure regimes, thereby influencing compaction intensity and pore preservation. The stress field governs fracture development and reservoir deformation, providing the critical link between tectonic processes and reservoir evolution. The fluid field serves as the principal medium for mass and energy transport, driving fluid-rock interactions and deep reservoir modification. Meanwhile, the chemical field determines mineral stability and reaction pathways, directly influencing mineral dissolution, precipitation, and pore evolution.

More importantly, these fields do not operate independently but interact through continuous feedback mechanisms. Variations in stress influence fracture development and fluid migration (Yan et al., 2025); fluid circulation modifies the chemical environment and promotes mineral reactions (Antonellini et al., 2025); thermal history and events fundamentally determine reaction rates (Gac et al., 2014); these reactions alter the mechanical properties of the rock (Yan et al., 2022), which in turn affect the stress distribution and subsequent reservoir evolution. Consequently, ultra-deep reservoir formation should not be viewed as a simple burial-diagenetic process, but rather as the progressive reorganization of an open reservoir-forming system driven by multi-field coupling.

From this perspective, the occurrence of high-quality ultra-deep reservoirs depends not only on the preservation or generation of pore space, but also on the effective configuration and co-evolution of pores, fractures, and fluids throughout geological history. Accordingly, future reservoir prediction should move beyond identifying individual diagenetic mechanisms and instead focus on recognizing the key controls governing the evolution of the reservoir-forming system.

5. Future directions: Toward the science of reservoir-forming systems

Future research on ultra-deep clastic reservoirs requires three fundamental shifts in perspective: from depth-based classification to diagenetic-state characterization, from pore-oriented studies to reservoir effectiveness, and from investigations of diagenetic processes to multi-field coupling. Particular emphasis should be placed on understanding the coupled evolution of the mass, thermal, pressure, stress, fluid, and chemical fields, as well as the mechanisms of stress-fluid-rock interaction that govern reservoir restructuring under ultra-deep conditions.

Ultimately, a comprehensive theory of reservoir-forming systems should be established for ultra-deep hydrocarbon exploration. Such a framework would move beyond predicting pore occurrence alone to predicting the evolution and spatial distribution of reservoir-forming systems, thereby providing a new theoretical basis for the evaluation and prediction of high-quality ultra-deep reservoirs.

6. Conclusions

Research on high-quality deep and ultra-deep clastic reservoirs has evolved from studies of porosity loss, pore preservation, and secondary pore generation toward an integrated understanding based on multi-field coupling. Conventional pore evolution models are becoming increasingly inadequate for explaining the formation of high-quality ultra-deep reservoirs. It is suggested that ultra-deep reservoirs should not be regarded simply as a deeper continuation of conventional deep reservoirs, but rather as a distinct geological regime characterized by extreme temperatures, pressures, and tectonic stresses, where reservoir evolution may be governed by physical and chemical principles fundamentally different from those operating in conventional deep settings.

Accordingly, future research should move beyond pore evolution toward the study of reservoir-forming systems, with particular emphasis on the coupled interactions among the mass, thermal, pressure, stress, fluid, and chemical fields. More importantly, recognizing the unique geological characteristics of ultra-deep reservoirs may provide the conceptual foundation for an emerging discipline of Ultra-deep Reservoir Geology, within which the reservoir-forming system can serve as a unifying theoretical framework for understanding, evaluating, and predicting high-quality reservoirs in the deep subsurface.

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Conflicts of interest

The authors declare no competing interest.

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