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Perspective

Multi-field coupling controls the formation and evolution of deep reservoirs

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Abstract:
Following the maturation of shallow and medium-depth exploration, the petroleum industry is transitioning its focus to deep and ultra-deep formations. Field evidence shows that, even under extreme conditions of high temperature, high pore pressure, and high stress, some reservoirs retain anomalously high porosity and permeability, contradicting traditional compaction models. This paradox can be better explained through multi-field coupling, where temperature, pore pressure, and stress interact competitively and cooperatively to reshape compaction, fracture behavior, and fluid-rock interactions. Such interactions may induce brittle–ductile transitions that form semi-ductile permeability corridors, or cause localized enrichment when stress contrasts restrict fracture propagation and fluid accumulation promotes episodic reactivation. These insights shift the interpretation of deep reservoirs from single-factor models to a coupling-based framework, offering new directions for evaluation and exploration.

1. Introduction

With the progressive maturity of shallow and medium-depth exploration, the global petroleum industry is accelerating into deep and ultra-deep formations, which have now emerged as a strategic frontier for reserve replacement (Sun et al., 2013; Pang et al., 2022). By the end of 2020, nearly two thousand deep oil and gas fields had been discovered worldwide, with their contribution to production rising sharply in recent decades, underscoring their growing role in the global energy landscape (Hao, 2022; Cao et al., 2023).

Conventional models predict that porosity and permeability decline monotonically with burial, rendering ultra-deep reservoirs ineffective (Dasgupta and Mukherjee, 2021). However, exploration evidence consistently contradicts this expectation. In the Tarim Basin, clastic reservoirs retain measurable porosity at depths of 6-8 km, and similar anomalies are observed in Sichuan carbonates and Gulf of Mexico sandstones (Liu et al., 2025). These observations diverge markedly from the predictions of compaction-driven models (Fig. 1). Proposed mechanisms include preservation of overpressure, porosity enhancement through mineral dissolution, and porosity generation by tectonic fracturing. While each of these mechanisms accounts for certain aspects of the process, none can fully elucidate why reservoirs remain stable under extreme conditions of elevated temperature, high pore pressure, and intense stress, nor can they adequately explain the characteristic patchy, banded, or lens-shaped distribution commonly observed.

Resolving this paradox requires moving from single-factor interpretations to a multi-field coupling perspective, in which temperature, pore pressure, and stress act competitively and cooperatively to govern reservoir evolution. This perspective

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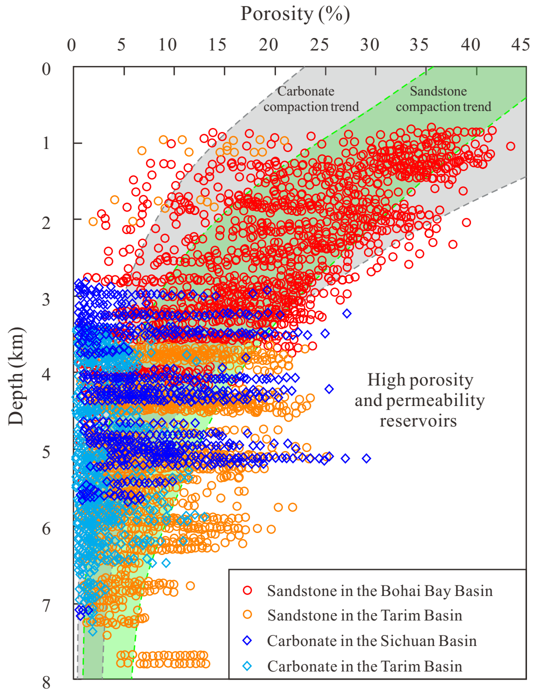

Fig. 1. Depth–porosity relationships of deep and ultra-deep reservoirs from representative basins in China, modified after Pang et al. (2020) and Cao et al. (2022).

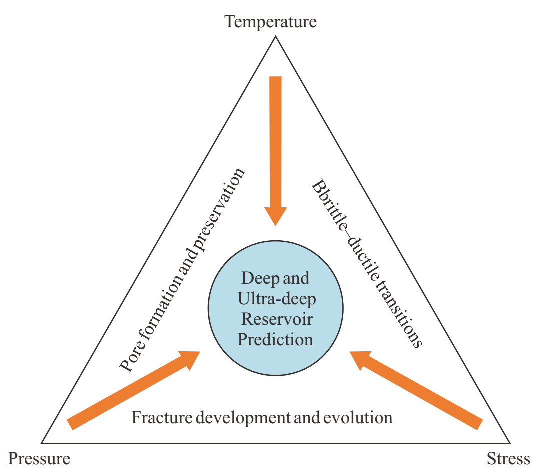

Fig. 2. Conceptual ternary diagram illustrating the controls of multi-field coupling on deep and ultra-deep reservoir prediction.

explains the persistence and heterogeneity of deep reservoirs. It highlights the importance of brittle-ductile transition zones, where microfracture networks enhance permeability. At the same time, localized processes may also operate, in which stress contrasts hinder fracture propagation, promote fluid accumulation, and trigger episodic reactivation that enhances permeability. Taken together, these perspectives establish a conceptual foundation for reinterpreting the evolution of deep reservoirs and for informing future exploration strategies.

2. Mechanisms of multi-field coupling in deep reservoirs

The long-term stability of deep reservoirs cannot be explained by single-factor models alone, but emerges from the coupled interactions among temperature, pore pressure, and stress. Through the interplay of competition and cooperation, these fields collectively reshape compaction, fracture dynamics, and fluid-rock interactions (Gou et al., 2019; Xu et al., 2024). High temperature accelerates mineral dissolution while also softening grains and promoting creep, pushing the system toward ductility. While elevated pore pressure reduces effective stress and contributes to the preservation of pore structures, it simultaneously magnifies tensile stresses at fracture tips, making brittle rupture more likely. High stress enhances compaction and pressure solution, suppressing tensile cracking while promoting plastic flow. The interplay of these processes promotes the evolution of reservoirs into brittle-ductile transition regimes, characterized by the simultaneous presence of brittle and ductile deformation. In such semi-ductile zones, microfracture networks emerge, enhancing connectivity and permeability by more than an order of magnitude (Meyer et al., 2024). These emergent features provide a physical explanation for why reservoirs can remain effective under extreme burial conditions.

The imprint of multi-field coupling is clearly reflected in pore and fracture types. Temperature-stress coupling produces pressure-solution seams, which progressively reduce residual intergranular pores and thereby characterize the evolution of deep clastic reservoirs. Pore pressure-stress coupling governs the initiation, orientation, and reactivation of tectonic fractures, controlling whether they remain sealed or act as long-lived conduits (Liu et al., 2024). Temperature-pressure coupling promotes dissolution pores and inhibits re-precipitation. This combined effect prolongs pore survival and extends the depth range of effective reservoirs. Multi-field coupling accounts for the coexistence of residual pores, dissolution voids, and tectonic fractures in ultra-deep reservoirs (Fig. 2).

Field evidence demonstrates how multi-field coupling manifests differently across basins. In the Tarim Basin, clastic reservoirs of the Bashijiqike Formation (6-8 km) are dominated by residual intergranular pores. Secondary dissolution pores and microfractures occur but play a subordinate role. Strong compaction and pressure solution under high stress and temperature highlight temperature-stress coupling as the primary control. In the Sichuan Basin, ultra-deep carbonates develop fracture-dissolution composites where high pore pressure sustains fracture openness and stress fields dictate orientation, underscoring the importance of pore pressure-stress coupling. The Gulf of Mexico presents another pattern, as deep-water sandstones retain anomalously high porosity (> 30%) at depths exceeding 7 km. This anomaly is best explained by temperature-pressure coupling, where high temperature accelerates dissolution while overpressure delays cementation. Studies on the Longmaxi Shale in Sichuan, together with experimental evidence, reveal that the combined action of temperature, pore pressure, and stress can drive rocks into semi-ductile regimes. Microfracture networks formed within brittle-ductile transition zones can enhance permeability by orders of magnitude, offering a unifying explanation for the persistence of reservoir quality under extreme "three-high" conditions.

In addition to the recognized coupling effects, a localized process may occur in which stress contrasts hinder fracture propagation and promote fluid accumulation ahead of barriers. Under high temperature and elevated pore pressure, trapped fluids destabilize fractures and enhance dissolution. These processes weaken the surrounding rock and increase the likelihood of episodic reactivation. Temporary blockage, chemical alteration by fluids, and fracture opening act together as a sequence. This sequence provides a plausible explanation for the banded or lens-shaped enrichment zones observed in ultra-deep reservoirs.

3. Conclusions

Deep and ultra-deep reservoirs persist under extreme "three-high" conditions through the coupled action of temperature, pore pressure, and stress. Evidence from Tarim, Sichuan, and the Gulf of Mexico shows that different modes of coupling dominate in different basins, yet all point to the same principle, which is that reservoir effectiveness is controlled by multi-field interactions. A critical outcome of this interplay is the brittle-ductile transition zone, where semi-ductile microfracture networks generate relative high-permeability corridors and help reconcile the paradox of reservoir persistence at great depths. Beyond the brittle-ductile transition, localized processes may also operate. In such cases, stress contrasts hinder fracture propagation, fluids accumulate ahead of barriers, and episodic reactivation enhances permeability. Though conceptual, this mechanism offers a plausible explanation for the patchy distribution of effective reservoirs in ultra-deep domains. Future work should prioritize experimental platforms for multi-field coupling, coupled numerical simulations, and in-situ observations of deep reservoir conditions and petrophysical evolution. These efforts will help clarify how multi-field interactions control the formation and persistence of deep reservoirs.

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Conflict of interest

The authors declare no competing interest.

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