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Perspective

# Multi-sphere interactions driven differential formation of the whole petroleum system

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**Abstract:**
Using the theories of multi-field coupling within a multi-sphere interaction framework and the Whole Petroleum System, this study investigates the formation, distribution and enrichment of hydrocarbon resources, promoting a shift in exploration philosophy from a singular to an integrated approach. By integrating disciplines such as geochemistry, geodynamics and structural geology, it systematically analyzes the coupling effects of tectonic stress, thermal, pressure and fluid potential fields in sedimentary basins and their controlling mechanisms on hydrocarbon generation, migration and accumulation. Combined with typical case studies from various basins, the distribution patterns of conventional, tight and shale oil and gas are revealed. The results demonstrate that multi-sphere interactions govern the ordered distribution of different hydrocarbon types by influencing the accumulation process, thereby establishing a hydrocarbon accumulation model described as "Spheres control Fields, then Fields control Thresholds, and Thresholds define Distribution". This theoretical framework aids in enhancing exploration efficiency and optimizing resource development strategies, providing novel insights and perspectives for future petroleum exploration.

## 1. Introduction

Since the beginning of this century, in-depth research on oil and gas exploration and development has continuously expanded in terms of reservoir types. The focus of exploration has undergone significant shifts: firstly, from structural reservoirs to stratigraphic-lithological reservoirs, secondly, from conventional to unconventional resources, and conceptually, from the petroleum system to the Whole Petroleum System (WPS). A new trend has emerged in petroleum geology theory: understanding hydrocarbon formation and enrichment in sedimentary basins from the perspective of Earth system evolution and multi-sphere interactions. Interdisciplinary studies integrating geochemistry, geodynamics, structural geology, and sedimentology revealed that mantle processes drive the movement and collision of continental blocks, thereby controlling the tectonic evolution of sedimentary basins. Meanwhile, interactions within the Earth's surface spheres primarily govern the enrichment and evolution of organic matter. Material cycling and energy exchange among the Earth's multi-spheres are the fundamental drivers of the spatiotemporal evolution of the tectonic stress field, thermal field, pressure field and fluid potential field. Furthermore, the multi-field coupling of tecton

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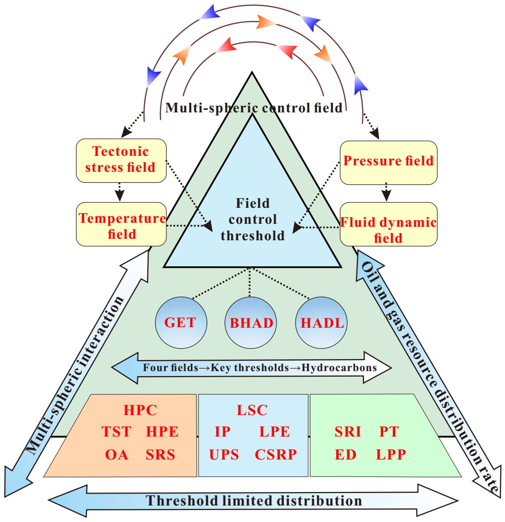


**Fig. 1**. Conceptual model of multi-field coupling and the WPS under multi-sphere interactions.

-ic stress, thermal, pressure and fluid potential fields within sedimentary basins profoundly influences the processes of hydrocarbon generation, migration and accumulation (Fig. 1).

Under the framework of multi-sphere interactions, the hydrocarbon accumulation process in sedimentary basins is no longer governed by isolated factors but results from the interplay of multiple dynamic mechanisms. The combined effects of deep dynamics, crust-mantle heat transfer, tectonic stress, and hydrodynamic forces collectively determine the hydrocarbon generation environment, reservoir properties, and enrichment patterns (Broadley et al., 2022). For instance, the structural framework and reservoir development of sedimentary basins are controlled by the tectonic stress field; organic matter maturity and hydrocarbon migration pathways are governed by the thermal and pressure fields; and the accumulation of hydrocarbons within reservoirs is driven directly by the fluid potential field.

The theories of multi-sphere interactions and the WPS have elucidated the distribution patterns and accumulation mechanisms of diverse hydrocarbon resources. The paradigm shift in exploration philosophy from the conventional petroleum system concept to the integrated WPS theory has facilitated China's major discoveries in ultra-deep hydrocarbons and continental shale oil over the past five years, heralding a new upsurge in petroleum exploration (Jia et al., 2024; Zhu et al., 2025). From the perspective of Earth system science, this paper systematically examines the influence of multi-field coupling on hydrocarbon formation and enrichment on the basis of the WPS framework, aiming to promote the efficient exploration and development of hydrocarbon resources.

## 2. Sphere interactions controlling the formation and evolution of the "four fields"

The Earth as a dynamic system of coupled multi-spheres derives the fundamental driving forces for the formation and evolution of basin-scale tectonic stress, thermal, pressure and fluid potential fields from the material-energy exchanges and dynamic processes between its internal spheres (Tao et al., 2025) (Fig. 1). Acting as the core mechanism, deep-seated dynamic processes directly or indirectly shape the multi-field configuration at the basin scale via trans-sphere tectonic effects.

### *2.1 Tectonic stress field*

The regional tectonic stress field and its orientation are a direct manifestation of lithospheric-scale plate motions. In Eastern China, deep-seated dynamic processes have governed the formation and evolution of Meso-Cenozoic rift basins. In Western China, the collision between the Indian and Eurasian Plates and subsequent intracontinental subduction have shaped the tectonic stress fields of compressional basins. These deep processes transmit stresses through plate boundaries, resulting in multiple phases of tectonic inversion in basins.

### *2.2 Thermal Field*

The variation in terrestrial heat flow across different basin types directly reflects the distribution of the Earth's internal thermal state, with its magnitude controlled by the deep crust-mantle structure. In Eastern China, influenced by the subduction of the Pacific Plate, a "hot mantle-cold crust" configuration is widely developed, where significant mantle-derived heat flow results in elevated surface heat flow, as observed in the Bohai Bay Basin. In contrast, central-western basins typically exhibit a "hot crust-cold mantle" characteristic, with geothermal gradients primarily governed by heat production from radioactive elements within the crust. Such crust-mantle structural disparities dictate the thermal evolution of basins and the hydrocarbon generation potential of source rocks. Deep-sourced heat, transferred via both lithospheric thermal conduction and the ascent of deep fluids, plays a critical role in driving hydrocarbon generation.

### *2.3 Pressure Field*

The formation and distribution of the pressure field are not isolated phenomena but result from the dynamic coupling of the thermal and tectonic stress fields under multi-sphere interactions. Material exchange and energy transfer between spheres modulate the intensity of this coupling, thereby influencing the spatiotemporal evolution of the pressure field (Tao et al., 2025; Zhu et al., 2025). Furthermore, deep dynamic processes, such as mantle plume upwelling or plate subduction, alter the geothermal gradient, affecting the hydrocarbon generation rate in source rocks and the volume of generated fluids. This provides the material basis for overpressure development, while tectonic stress concurrently modifies the physical state of the strata (Brink, 2009). Consequently, the spatial distribution of the pressure field, particularly the formation and distribution of over-pressured compartments, reflects the coupling of deep thermal effects and crustal stress within specific tectonic settings, with its evolutionary history being intrinsically linked to the tectonic-thermal history of the basin.

### *2.4 Fluid Potential Field*

The fluid potential field is controlled by and results from the coupling of the thermal, pressure and stress fields. It forms through energy transfer, material exchange and mechanical response. The thermal field, shaped by deep processes, determines the initial volume of hydrocarbons generated from source rocks, while the stress field governs fluid migration pathways. Together, they define the fluid potential regime within the basin, driving hydrocarbons from areas of high to low potential. Moreover, the upwelling of deep fluids introduces both material and energy into the basin. Their inherently over-pressured characteristic can alter the existing fluid potential field, either establishing independent fluid systems or mixing with basinal fluids, collectively influencing hydrocarbon migration and accumulation processes.

In summary, multi-sphere interactions, particularly deep-seated dynamic processes, govern the formation and evolution of the tectonic stress, thermal, pressure and fluid potential fields, establishing an interconnected and dynamically evolving multi-field coupling system.

## 3. "Four-field coupling" controls hydrocarbon accumulation formation and distribution

The circulation of material and energy between different spheres within the Earth system plays a critical role in hydrocarbon generation (Fig. 1). In terms of the hydrocarbon generation process in petroliferous basins, multi-field coupling serves as the core controlling mechanism. Its spatiotemporal evolution and dynamic matching relationships govern the entire sequence of events, from hydrocarbon formation and reservoir development to accumulation.

### *3.1 "Four-field coupling" controls the hydrocarbon generation process*

The tectonic stress field governs basin structural evolution through compression and extension, directly controlling source rock burial depth and organic matter distribution. The thermal field serves as the key factor for organic matter maturation, governing the conversion of organic matter into hydrocarbons by influencing the heating extent of source rocks. Basins with different heat flow values exhibit significant differences in hydrocarbon generation and expulsion thresholds. Under abnormal pressure conditions, hydrocarbon generation rates can be suppressed. Furthermore, in deep tectonic settings, pressure field variations control the critical conditions for hydrocarbon generation, thereby influencing the accumulation of primary hydrocarbon yields (Hu et al., 2024).

### *3.2 "Four-field coupling" controls reservoir formation processes*

The development of hydrocarbon accumulations requires high-quality reservoir-seal assemblages, with multi-field coupling serving as the key controlling factor for both reservoir properties and sealing conditions. Rock fracturing and deformation are dominated by the tectonic stress field, reshaping the pore-fracture system of reservoirs through folding and faulting. Meanwhile, elevated formation temperatures reduce fluid viscosity, thereby enhancing the dissolution capacity of fluids and indirectly improving reservoir effectiveness (Li et al., 2019). This thermal effect further influences the lower limit of buoyancy accumulation and the fundamental accumulation boundary in basins with varying heat flow values. The pressure field governs reservoir confinement, as exemplified by the over-pressured compartments (with pressure coefficients of 1.5-1.8) in the deep Mahu Sag of the Junggar Basin, which effectively restrict the outward migration of hydrocarbons (Zhang et al., 2023).

### *3.3 "Four-field coupling" controls hydrocarbon accumulation dynamics*

The fluid potential field serves as the core dynamic system for hydrocarbon accumulation, determining migration pathways, accumulation efficiency, and reservoir stability. The tectonic stress field generates fluid potential gradients, creating preferential migration pathways. A prime example is the extensional fault system in the Jiyang Depression of the Bohai Bay Basin, which, under stress-driven forces, acts as a conduit for vertical hydrocarbon migration, facilitating the transport of hydrocarbons from Paleogene source rocks to shallow reservoirs (Feng et al., 2023). The thermal field influences migration dynamics by altering fluid properties, thereby reducing hydrocarbon flow resistance. The pressure field establishes a dynamic equilibrium that not only sustains the driving force for continuous hydrocarbon charging but also prevents leakage due to reservoir fracturing. This is well exemplified by the Sulige Gas Field in the Ordos Basin, which exhibits normal to weakly over-pressured characteristics (Li et al., 2022).

In summary, the formation and distribution of hydrocarbons represent a complex process governed by the interactions of tectonic stress, thermal, pressure and fluid potential fields, which collectively control hydrocarbon generation, migration and accumulation.

## 4. Distribution patterns and accumulation boundaries of conventional-tight-shale oil and gas

In petroliferous basins, conventional, tight and shale reservoirs do not develop in isolation but are organically interconnected within the WPS. Their ordered distribution follows the core paradigm of "Spheres control Fields, then Fields control Thresholds, and Thresholds define Distribution": multi-sphere interactions govern the coupled evolution of the tectonic stress, thermal, pressure and fluid potential fields, and the resulting multi-field coupling effects in turn regulate the entire process of hydrocarbon generation, migration and accumulation.

Hydrocarbon accumulation thresholds collectively determine the sequential pattern of hydrocarbon accumulation under the coupling effects of the "Four Fields". The hydrocarbon generation-expulsion threshold marks the onset of effective hydrocarbon supply from source rocks, representing the starting point of accumulation and determining whether source rocks can provide sufficient hydrocarbons for the petroleum system. The formation of conventional and tight reservoirs is separated by buoyancy-driven hydrocarbon accumulation depth. For unconventional accumulations, the hydrocarbon accumulation depth limit controls the maximum burial depth. With increasing depth, the driving forces for hydrocarbon enrichment gradually weaken, thereby limiting further accumulation (Pang et al., 2022). Therefore, hydrocarbon accumulation boundaries are comprehensively determined by these dynamic conditions, influencing the type, distribution and scale of hydrocarbon reservoirs (Hu et al., 2022). Conventional reservoirs developing above the hydrocarbon expulsion threshold typically exhibit the characteristics of "high-position convergence, top-sealed trapping, high-porosity enrichment, overpressure accumulation, and source-reservoir separation". Tight reservoirs, occurring between the hydrocarbon expulsion threshold and the buoyancy-driven hydrocarbon accumulation depth, display a distribution pattern of "low-sag convergence, inverted placement, low-porosity enrichment, under-pressure stability, and close source-reservoir proximity". Shale reservoirs, developed within source rocks below the conventional buoyancy-dominated hydrocarbon accumulation zone yet above the lower depth limit for accumulation, are characterized by "source-reservoir integration, pervasive tightness, extensive distribution, and low permeability-productivity" (Pang et al., 2022).

In summary, the dynamic transition boundaries of hydrocarbon accumulation represent the key mechanism that reveals how the "Four Fields" couple to control the ordered distribution of conventional, tight and shale hydrocarbons, ultimately forming the systematic distribution model within the WPS.

## 5. Conclusions and prospects

On the basis of the WPS theory, future efforts will shift from targeting individual hydrocarbon types toward an integrated exploration and development approach for conventional, tight and shale resources. By applying the ordered distribution model of these hydrocarbon types and synthesizing the full processes of generation, migration and accumulation, this approach is expected to significantly enhance the efficiency of hydrocarbon resource exploration and development.

The thermal field plays a critical role in hydrocarbon generation, migration and accumulation. High heat flow areas favor rapid hydrocarbon generation but may exhibit lower enrichment efficiency; moderate heat flow regions tend to offer more balanced hydrocarbon distribution suitable for sustained development; whereas low heat flow areas are characterized by slow generation rates and challenging accumulation conditions. Future exploration strategies must therefore incorporate basin-specific thermal field characteristics, comprehensively considering the coupled effects of terrestrial heat flow, tectonic stress and other dynamic fields to optimize resource exploitation and advance the efficient utilization of hydrocarbon resources.

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## Conflicts of interest

The authors declare no competing interest.



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