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Perspective

Whole petroleum system theory and new directions for petroleum geology development

Tao Hu[1,2], Xiongqi Pang[1,2]*, Fujie Jiang[1,2]

[1]*National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, P. R. China*
[2]*College of Geosciences, China University of Petroleum, Beijing 102249, P. R. China*

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Abstract:
As the global petroleum exploration domain gradually shifts from conventional to unconventional hydrocarbon resources, the classical petroleum system theory faces new challenges in terms of guiding the deepening exploration practices in the petroleum industry. After years of research, Chengzao Jia proposed the whole petroleum system concept and established an orderly distribution model for the coexistence of conventional and unconventional petroleum, which provides a new theoretical framework for the joint assessment and integrated exploration of conventional and unconventional petroleum resources. In this context, the 1st International Symposium on Whole Petroleum System Theory and New Directions for Petroleum Geology Development was held in Beijing in October 2-3, 2023. The theme was "Whole petroleum system theory and new frontiers in petroleum exploration". Experts engaged in in-depth discussions on the progress of whole petroleum system theory and development directions of petroleum geology; they systematically reviewed the new theory developments and advances in sequence stratigraphy, tight oil and gas, shale oil and gas reservoir characteristics, genetic mechanisms, and development mechanisms. The conference also proposed unified genetic models for conventional and unconventional petroleum resources, and novel methods and technologies for joint assessment. Furthermore, it also included case studies on the whole petroleum system in clastic and carbonate formations in oil and gas basins, challenges, opportunities, and new directions in the development of petroleum geology. This symposium provided a valuable opportunity for the petroleum geology community to gain a deep understanding of the "whole petroleum system theory" and to summarize and refine the development directions of petroleum geology. Undoubtedly, this event contributes to the advancement of the whole petroleum system theory, guiding the development of petroleum geology theory and further promoting the joint assessment and integrated future development and utilization of conventional and unconventional petroleum resources.

1. Introduction

The classical petroleum system theory, from source rock to trap, integrates the significant progress of petroleum geology researches, such as buoyancy accumulation, trap control, organic hydrocarbon generation, and source control oil and gas distribution, which play important guiding roles in petroleum exploration practice (Leslie and Magoon, 2004). However, as the field of oil and gas exploration continues to expand to unconventional oil and gas resources, the classical theory faces increasing challenges in further petroleum exploration guidance. After years of exploration, Chinese scholars put forward a new concept of the whole petroleum system and established an orderly distribution model of conventional and unconventional oil and gas joint symbiosis, providing a new theoretical framework and technical guidance for the joint evaluation and integrated exploration of conventional and unconventional petroleum under complex geological conditions. To promote the deepening development of petroleum geology theory, boost the rapid growth of petroleum reserves in China and ensure the training of relevant talents, the 1st International

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*Corresponding author.
E-mail address: thu@cup.edu.cn (T. Hu); pangxq@cup.edu.cn (X. Pang); jiangfj@cup.edu.cn (F. Jiang).

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Symposium on Whole Petroleum System Theory and New Directions for Petroleum Geology Development was held at China University of Petroleum (Beijing) on October 2-3, 2023. The theme was "whole petroleum system theory and new frontiers in petroleum exploration", and a total of 325 scholars presented their latest achievements in scientific researches and petroleum exploration. Accordingly, this paper summarizes the main advances in petroleum geology theory and highlights the new directions for petroleum geology development.

2. Main advances

New progress in the study of whole petroleum system theory and order accumulation model. The whole petroleum system theory was a major theoretical breakthrough in the petroleum system, which unifies the whole process of generation, discharge, migration, and accumulation of conventional and unconventional oil and gas resources. At the meeting, Chengzao Jia, the main founder of this theory, systematically introduced the connection and innovation between the theory and the traditional theory of petroleum geology and the development process (Jia, 2017). Subsequently, taking Cangdong Sag of Huanghua Depression, Bohai Bay Basin as an example, Xianzheng Zhao presented an integrated and orderly development model of multi-layer and conventional and unconventional reservoirs in the whole petroleum system, proposed a multi-layer coupling conventional and unconventional integrated orderly accumulation concept, and introduced a major exploration breakthrough (Zhao et al., 2022). Conducting a study on the Junggar Basin, Yong Tang clarified the characteristics of full-grained sequence deposition and sequence genesis of conventional-unconventional full-type reservoirs, revealed the 'source-reservoir coupling' of the whole petroleum system and the orderly symbiosis mechanism of conventional-unconventional reservoirs, and achieved two major breakthroughs in petroleum exploration in the northern and southern Mahu Sag under the guidance of the whole petroleum system theory (Tang et al., 2022). Taking the terrestrial strata of the Sichuan Basin as an example, Long Wen proposed a orderly distributed gas system originated from coal source rocks of the Xujiahe Formation, including the shale gas within, tight gas near, and structural conventional - tight gas far from the source, and established the terrestrial whole petroleum system model in Sichuan Basin (Wen et al., 2023). Investigated from the dual features of source control on petroleum distribution and source-reservoir symbiotic system in petroleum accumulation, Zhi Yang establisded the orderly symbiotic enrichment of conventional and unconventional petroleum model (Yang and Zou, 2022).

Reservoir characteristics, genetic mechanisms, and development mechanisms of tight and shale oil and gas. The discovery and further large-scale exploitation of unconventional petroleum comprise significant milestones in the face of conventional petroleum exploration. This expansion has broadened the field of oil and gas exploration, leading to a 2- to 5-fold increase in petroleum resources and bringing vast development prospects. Yan Song introduced the essence of the whole petroleum system, in which "whole" refers to the "entire" underground oil and gas accumulation (both conventional and unconventional petroleum), and does not constitute "all" petroleum geological research. She elaborated on this new research approach and clarified the role of self-sealing in the distribution of unconventional oil and gas (Jia et al., 2023a, 2023b). Ronghu Zhang explored the characteristics of reservoirs and petroleum accumulations in the Cenozoic whole petroleum system in the Kuqa Depression, Tarim Basin. He specified the driving forces for differential petroleum accumulation within the whole petroleum system from bottom to top, which were the intra-source molecular forces and the buoyancy of petroleum away from the source rocks (Zhang et al., 2022). Xiaorong Luo introduced the composition and function of the transport system within the whole petroleum system, arguing that the orderly distribution and gradual evolution of conventional and unconventional petroleum in the system had uniformity in fluid dynamics. He highlighted that conducting quantitative research on the mechanisms and processes of petroleum migration and accumulation within and between different types of reservoirs is crucial for a better understanding of the petroleum enrichment laws in the whole petroleum system and the evaluation of various types of petroleum resources (Luo et al., 2023; Hu et al., 2024). Keyu Liu proposed the scientific considerations related to the formation and evolution of deep oil and gas reservoirs, which include mass balance, energy conservation, the mode and dynamics of deep oil and gas migration, and the dynamic evolution process of reservoir formation. Using the Mid-Lower Member of the Craton Formation as an example, he established a model for the formation of deep oil and gas reservoirs (Yang et al., 2021).

Unified genetic models for conventional and unconventional petroleum and new methods and technologies for the joint evaluation of conventional and unconventional petroleum resources. Conventional and unconventional reservoirs exhibit significant differences in terms of correlation, distribution boundaries and controlling factors (Pang et al., 2021a; Hu et al., 2022; Jin, 2023). Introducing new methods and technologies for the joint evaluation of these two resources is conducive to refining and developing petroleum reservoir formation theories, advancing current petroleum exploration processes, and improving exploration efficiency. Based on the whole petroleum system theory, Xiongqi Pang established a new method and technology for evaluating natural gas hydrate resources: he systematically assessed the global and South China Sea natural gas hydrate resources and conducted reliability verification, yielding a novel understanding that natural gas hydrates are unlikely to become a major future energy source for humanity. He emphasized the need to guide current exploration and development strategies based on updated assessments rather than relying on earlier natural gas hydrate resource evaluations (Pang et al., 2021b). Based on the hydrocarbon source rocks of the Fengcheng Formation in the Mahu Sag, Junggar Basin, Jian Cao established an oil and gas generation sequence within the whole petroleum system, which serves as a reference for the systematic evaluation of resources within this system (Tao et al., 2019). Fujie Jiang dissected the ancient Cenozoic whole petroleum system in

the Kaping Sag, Pearl River Mouth Basin, establishing a differential supply, segmented transport, and faulted accumulation model. He concluded that conventional petroleum resources account for 33% within the whole petroleum system, indicating the enormous exploration potential for unconventional petroleum resources (Jiang et al., 2023). Chunfang Cai systematically reviewed researches on the deep and ultra-deep sulfur-involved organic-inorganic interactions and petroleum sources. He suggested that sulfur isotope composition had a wide application prospect in the oil and gas source and late-stage secondary alteration within the whole petroleum system (Cai et al., 2022a). Haikuan Nie studied the Wufeng Formation and Longmaxi Formation in the Sichuan Basin and discussed the exploration and development potential of deep shale gas (Nie et al., 2023).

Case studies of whole petroleum system researches on clastic and carbonate reservoirs in petroliferous basins. Clastic and carbonate reservoirs differ significantly in their evolution process and resource distribution. Clarifying the main controlling factors and enrichment models for different types of reservoirs within the whole petroleum system can certainly guide further petroleum exploration. Xusheng Guo discussed the current situation and progress of marine petroleum system exploration in the Sichuan Basin, analyzed the characteristics of petroleum system division and reservoir formation, summarized the reservoir formation and enrichment laws and exploration direction of marine petroleum, and claimed that more resources would be made accessible by adhering to the concept of reservoir formation in the whole petroleum system and the exploration idea of conventional-unconventional integration (Guo et al., 2020); Jinhua Fu clarified the reservoir control factors by systematically dissecting the petroleum system of the Triassic Yanchang Formation in the Ordos Basin, and proposed four directions for further development: the Chang 7 shale oil is a strategic area for high-quality development; Chang 6 and Chang 8 remain the basic foundation for recent large-scale storage and production; the western new area and the lower combination of the new layer system are the important succession fields; and shallow formations are the focus for improving quality and efficiency from the source (Fu et al., 2023). Guoxin Li dissected the Paleogene-Neogene whole petroleum system in the Chaixi Depression, Qaidam Basin, and proposed exploration directions in lithological, structural and shale reservoirs (Li et al., 2022). Dongming Zhi implemented the exploration achievements in the Junggar Basin, North Xinjiang Basin, guided by the whole petroleum system. He held the view that applying petroleum system thinking and focusing on source-reservoir coupling could efficiently explore both conventional and unconventional petroleum resources (Zhi et al., 2021). Yong Song systematically analyzed the whole petroleum system of the Fengcheng Formation in the Western Depression, Junggar Basin, emphasized the transformation of traditional petroleum exploration concepts, analyzed the basic conditions for the formation of the whole petroleum system, and introduced recent exploration achievements and insights (Song et al., 2022). Xiaojun Wang introduced the basic conditions of the whole petroleum system in Songliao Basin, and found that the Upper Oil System was characterized by "homologous symbiosis, orderly distribution and differential enrichment" of all types of oil reservoirs, while the Lower Gas System featured the orderly aggregation of multiple types of gas reservoirs, including conventional gas, tight gas and shale gas (Zhang et al., 2023). Huimin Liu dissected the characteristics of the whole petroleum system in the Jiyang Depression. He emphasized that starting from the source was the foundation of basin exploration, and integrated exploration changes the oil and gas exploration process; he expanded the petroleum exploration space based on the whole petroleum system theory (Liu et al., 2022). Weilin Zhu analyzed the development trends of deepwater petroleum in passive continental margin basins. He asserted that passive continental margin deepwater petroleum resources exhibited great exploration potential, had relatively low exploration and development levels, and thus were an increasingly important focus for international oil companies (Zhu et al., 2017).

Challenges, opportunities and new directions for petroleum geology development. Performing researches on the whole petroleum system can address some longstanding global challenges in the petroleum industry and showcase the enormous development potential of petroleum resources, which should include the unified genetic classification of conventional and unconventional reservoirs, the prediction of the distribution of remaining resource potential, and the development prospects of natural gas hydrates. To this end, Zhijun Jin conducted a survey on the latest developments in shale oil researches worldwide, focusing on fine-grained sedimentation, hydrocarbon occurrence, and oil micro-migration (Jin et al., 2021). Combining this with China's progress in the exploration of continental shale oil, he compared and summarized the basic geological characteristics and differences between terrestrial and marine shale oil. He identified three key scientific issues facing shale oil exploration in China: the formation mechanism of fine-grained sedimentary rocks, the occurrence mechanism of continental shale oil, and the micro-migration mechanism of continental shale oil. He suggested focusing on these scientific issues, intensifying integrated geological-engineering research and technological breakthroughs to ensure the success of shale oil revolution in China (Jin et al., 2021). Furthermore, Fang Hao condensed four directions for petroleum geology development: the composition, structure and controlling factors of shale strata; organic-inorganic interactions and multi-phase hydrocarbon generation mechanisms; reservoir differentiation evolution and ultra-deep petroleum enrichment mechanisms; geological process-based whole petroleum system simulation technology. Conducting additional research in these areas will further enrich the theoretical system of petroleum geology (Hao and Zou, 2013). Quanyou Liu discussed the sources and enrichment characteristics of hydrogen and helium in geological strata, and suggested that the development of petroleum geology should focus on the Earth system (Wang et al., 2023). Guangyou Zhu analyzed four aspects of deep oil and gas exploration: the conditions and resource potential of hydrocarbon sources in ten-thousand-meter-deep layers, the origin and storage mechanism of dolomite, the mechanism of oil and gas accumulation and preservation, and the analysis of

billion-ton exploration areas. He subsequently proposed four main directions for the theoretical development of deep and ultra-deep layers: explaining the formation of ultra-long-life petroleum reservoirs, understanding how ultra-high-amplitude oil columns and wells with thousands of tons and million cubic meters of gas wells are formed, investigating whether one set of source rock in the Precambrian can form scale oil and gas resources, and examining whether the source, reservoir and seal are fundamental elements for reservoir formation (Yang et al., 2022; Zhu et al., 2023).

3. Conclusions

This paper reports on subjects discussed during the 1st International Symposium on Whole Petroleum System Theory and New Directions for Petroleum Geology Development. This conference was the first theoretical seminar held since the theory establishment of the whole petroleum system. Experts reported on the research progress of the whole petroleum system and the petroleum geology development from the aspects of theoretical progress, methods and technologies, and current challenges and opportunities, to improve the in-depth understanding of the new theory, directions and breakthroughs of petroleum geology. This academic seminar on the development direction of whole petroleum system theory and petroleum geology can play a significant role in promoting the theoretical development and practical applications of the whole petroleum system, a recently emerged platform that is conducive to explaining new theories simultaneously as well as the orderly distribution laws of conventional and unconventional petroleum resources. Facilitated by foreign and Chinese scholars alike, the deepening research and sustainable development of oil and gas, along with the improvement of theory, are expected to achieve a historic transformation in this field on a global scale.

Conflict of interest

The authors declare no competing interest.

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