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Perspective

Hydrocarbon accumulation and resources evaluation: Recent advances and current challenges

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Abstract:
Conventional petroleum exploration targets have become increasingly complex recently. Although geological research of unconventional oil and gas resources has received much attention in recent years, such resources also face many complex geological and scientific problems. In this context, the 8th International Symposium on Hydrocarbon Accumulation Mechanisms and Petroleum Resources Evaluation was held in Beijing from 21 to 23 October, 2022. Experts presented and discussed their latest research findings on this topic relating to both conventional and unconventional oil and gas resources. They also discussed various development strategies for the petroleum industry taking into account the global objectives of "carbon peaking and carbon neutrality" to mitigate the impacts of climate change. Six significant theoretical advances and some new technologies were introduced at this conference. These advances related to the "Whole Petroleum System" theory, shale oil and gas exploration, deep and ultra-deep petroleum exploitation, clean energy issues, and alternative types of unconventional oil and gas resources. In response to these technological advances, four major current challenges were identified. These challenges related to the petroleum industry's ongoing growth and development in the context of carbon-neutrality goals, the evolution of hydrocarbon laws relating to petroleum accumulations and their exploitation, organic and inorganic effects on petroleum generation and accumulation mechanisms, and artificial intelligence applications related to hydrocarbon prediction.

1. Introduction

The International Symposium on Hydrocarbon Accumulation Mechanisms and Petroleum Resources Evaluation (ISHAMPRE) was conceived with a view to addressing fundamental science and technology issues related to petroleum accumulation and resource evaluation in a global context. This symposium has been sponsored and generally scheduled once every four years since the 1st conference held in Beijing in October 1993 with the theme of "New Developments in Petroleum Exploration". The subsequent conferences have each focused on different topical themes. In 2022, in order to discuss the development strategy of petroleum industry in the context of carbon peaking and carbon neutrality, and to track international research trends and new development directions, the theme of the 8th ISHAMPRE was determined as "Carbon Neutrality and Petroleum Resources". With this theme the conference focused on the latest research progress in petroleum systems, petroleum resources in deep/ancient formations, and shale oil and gas generation and migration.

The conference delegates provided extensive and in-depth discussions concerning the latest research progress relating to carbon-neutrality objectives, new and cleaner methods and technologies for exploiting geological resources, reservoir-control mechanisms and resource evaluation relating to the whole petroleum system, hydrocarbon accumulation and resource potential in deep-ancient formations, unconventional hydrocarbon accumulation and geological evaluation. A total of 238 scholars presented reports to the conference, among

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which 39 academicians and specialists delivered invited reports. Additionally, 152 experts and graduate students provided invited reports and oral presentations at 6 sub-sessions, and 47 scholars and graduate students presented their latest scientific research achievements through poster sessions. The conference adopted a new mode of information delivery combining in-person and online presentations. This enabled more than 300 experts and scholars from 43 universities, institutes, and enterprises in China and around the world to participate in the conference offline, and the online live broadcasts were viewed more than 40,000 times.

2. Main advances in carbon neutrality and petroleum resources

(1) The "Whole Petroleum System" represents a major breakthrough (Jia et al., 2017) in the concept of "Petroleum System" analysis proposed by Magoon and Dow (1994). It unifies the whole process of generation, expulsion, migration and accumulation of conventional and unconventional hydrocarbon resources. During the conference, Prof. Chengzao Jia analyzed the continuous accumulation of unconventional oil and gas and conventional oil and gas traps from the perspective of the Whole Petroleum System (Jia et al., 2022). Prof. Xiongqi Pang elaborated on the hydrocarbon accumulation mechanisms of the Whole Petroleum System and the resource evaluation of natural gas hydrate (Pang et al., 2021). Prof. Changgui Xu focused on the hydrocarbon accumulation mechanism of strike-slip transition zones in China's offshore regions, and the associated exploration breakthroughs resulting in the discovery of large and medium oil and gas fields. These theoretical advances have confirmed that the "Whole Petroleum System" concept can provide new theoretical guidance and technical support relating to the prediction of the distribution and extent of conventional and unconventional oil and gas reservoirs. The concept represents a development direction for oil and gas geological research worthy of future attention.

(2) Shale oil and gas is the type of unconventional petroleum resource receiving most research and commercial attention at present. It has become an important strategic replacement of conventional petroleum resources, with rapid progress in theoretical and technological innovations and continuous breakthroughs relating to its exploration and development recently (Jin et al., 2021). Prof. Zhijun Jin systemically reviewed the theoretical and technological progress of shale oil in the world and pointed out the requirement of basial research, vital technology, and national policy requirements for the development of Chinese shale oil in the future. Prof. Wenzhi Zhao studied the conversion rate of organic matter, petroleum expulsion rate, and main enrichment types of shale oil in the Triassic Chang 7 shale formation, Ordos Basin (Zhao et al., 2018). Prof. Caineng Zou combined the current background to clarify the development trend of the petroleum industry moving from conventional to unconventional oil and gas exploitation (Zou et al., 2022); Prof. Fang Hao considered the differential enrichment mechanisms associated with shale gas resources (Hao and Zou, 2013). Prof. Xusheng Guo discussed the enrichment mechanism of continental shale oil. Professor Colin E. Snape discussed a new method for shale gas reserves evaluation for the Bowland Shale, U. K. (Whitelaw et al., 2019). Prof. Xiaofei Fu discussed the quantitative evaluation of shale oil occurrence and its application. Additionally, field experts such as Profs. Xianzheng Zhao, Xiaojun Wang, Xiangzeng Wang, presented case studies sharing exploration and development experiences of shale oil. A group of academic leaders and young scientists such as Profs. Maowen Li, Xiaomei Wang, Chenggang Xian, Jian Cao and Shu Jiang also exhibited the latest results of their ongoing research related to this topic.

(3) The distribution of deep and ultra-deep source rocks and reservoirs and the hydrocarbon accumulation assemblages related to them were considered, including the genetic mechanisms responsible for the diversity of petroleum resources recorded. Much progress has been made relating to geological theory, technology, and evaluation methods in the context of deep hydrocarbon accumulations, providing theoretical guidance for deep and ultra-deep petroleum exploration strategies. At the conference, Prof. Shuichang Zhang expounded on the formation and preservation mechanisms of marine ultra-deep oil and gas resources (Zhang et al., 2018). Prof. Keyu Liu discussed recent progress in the exploration of deep hydrocarbon accumulation resources in the Tarim Basin (Yang et al., 2021). Prof. Xiaorong Luo evaluated the reservoir effectiveness of deep clastic rocks. Prof. Lianbo Zeng discussed the hydrocarbon accumulation mechanisms of strike-slip faults in the Tarim Basin. Prof. Quanyou Liu addressed the hydrocarbon accumulation mechanisms associated with the action of deep fluid movements (Liu et al., 2019). Prof. Guangyou Zhu assessed the accumulation mechanisms in relation to deep multi-phase hydrocarbons and their implications for the resource potential in the Tarim Basin (Zhu et al., 2019).

(4) In the context of "carbon peaking and carbon neutrality", substantial efforts are required in petroleum exploration and development to find cleaner production technologies and reduce harmful atmospheric emissions. This involves identifying the key technologies appropriate for clean energy industrial systems, and focus on the promotion of the research and development in expanding and transferring petroleum-industry-related technologies to geothermal, hydrogen, and carbon industrial system. The carbon industry system is currently dominated by carbon capture, utilization and storage (CCUS), which are recognized by the international community to offer the potential to provide the most effective carbon emission reduction technology. At this conference, Prof. Steve Larter highlighted the latest progress in carbon sequestration and carbon reduction technologies (Silva et al., 2020). Prof. Zhangxin Chen reviewed the current situation, progress, challenges, prospects selected applications of CCUS technologies, and focused on the realization and application prospects for CCUS technologies in the future (Zhang et al., 2022). Prof. Nansheng Qiu presented geothermal research based on earth system analyses, considering the formation mechanisms relating to deep high temperature geothermal energy in eastern China as an example.

(5) In addition to shale oil and gas, alternative unconventional oil and gas resources include tight oil and gas, heavy oil,

and oil shale are also important types of unconventional oil and gas resources exploited around the world. Prof. Fariborz Goodarzi reviewed new research progress in relation to oil shale exploitation in Canada (Goodarzi et al., 2022). Prof. Simon George discussed a new formation mechanism of heavy oil from information provided from the study of fluid-inclusions data. Professor Jianhui Zeng discussed the key scientific issues of tight oil and gas accumulation. Drs. Erfan Abolghasemi and Pål Ø. Andersen discussed the influences of adsorption layer thickness and pore geometry on tight gas production.

(6) Breakthroughs in new ideas and technologies are likely to bring about major reforms in oil and gas exploration theory. Prof. Lichun Kuang discussed the evaluation methods of oil-bearing properties of continental shale oil. Prof. Shangxu Wang identified a lack of mesoscale theories and technologies currently applied in petroleum geophysical exploration, suggesting that the fusion of geological and geophysical information is an effective way to solve this problem. Prof. Xiongqi Pang provided a quantitative study on the evaluation of natural gas hydrate resources around the world and in the South China Sea. In addition, Profs. Hui Tian, Hamed Sanei, Bogoyavlensky V. I, Danis Nourgaliev, Bo Zhang and other scholars presented other innovative research ideas.

3. Current challenges

The mission and aspiration of Chinese petroleum geologists should be to strive to improve China's ability to obtain petroleum resources globally, increase oil and gas self-sufficiency, and narrow the gap between energy supply and demand. Combined with China's actual geological background and the distribution characteristics of petroleum resources, our current challenges are mainly manifested in four aspects:

(1) Hydrocarbon accumulation and petroleum resources evaluation under the background of "carbon peaking and carbon neutrality". This is a long-term problem that will take many years to adequately address. First of all, the priority should be to preferentially search for and utilize low-carbon oil and gas resources, especially natural gas. Additionally, it is necessary to strengthen researches on the genetic mechanisms and enrichment laws relation to hydrogen under natural conditions. It is also necessary to combine the exploitation of high-carbon heavy oil resources with effective processes of carbon removal to contribute to CCUS, and provide cleaner utilization possibilities for high-carbon heavy oil resources. Additional research is also required relating to organic carbon concentrations and improved dehydrogenation under high temperature conditions for source rock formation. This has the potential to reveal more precisely the carbon cycle conditions, mechanisms and laws that apply under natural conditions, and to inspire us to apply them more effectively in resource utilization.

(2) Hydrocarbon accumulation laws of the Whole Petroleum System and joint evaluation of multi-type petroleum resources. The comprehensive evaluation of the potential of different types of petroleum resources cannot be solved if the accumulation mechanisms and distribution laws of conventional and unconventional oil and gas continue to be investigated separately. The traditional Petroleum System theory from source rock to trap cannot effectively guide the unconventional oil and gas exploration and the efficient utilization of different types of petroleum resources. It is an inevitable requirement for the development of petroleum geological theory to include shale oil and gas within the source rock, tight oil and gas adjacent to source rocks, and conventional oil and gas migrated long distances from source rocks, in integrated theories that consider the formation and evolution of petroleum source rocks. The Whole Petroleum System offers the potential to do this by characterizing the whole process, considering all the controlling factors, and all types of resources. Research on the characteristics of the evolution process of the Whole Petroleum System are significant in that they reveal the differences and correlations of the formation mechanisms and distribution laws between conventional and unconventional petroleum reservoirs, between shallow and deep petroleum reservoirs, between early and late genetic petroleum reservoirs, and between carbonate and sandstone reservoirs (Hu et al., 2022). The approach offers substantial guidance relating to the research and development of different types of petroleum resources, the prediction of resource distributions, and identifying the appropriate evaluation technologies. It offers the potential to realize a transformation from tracking foreign hydrocarbon accumulation research to leading the development of global hydrocarbon accumulation analysis. Hence, it is considered worthwhile to further improve, deepen and develop the theory of the Whole Petroleum System and its practical applications.

(3) Organic-inorganic effects on deep petroleum generation and accumulation. Petroleum origin has been debated for several centuries. Although it is still inconclusive, there are strong indications that inorganic actions impact the generation and distribution processes involved in petroleum generation and accumulation. The theory of organic-inorganic effects has attracted substantial attention, especially under the conditions of high temperature and high pressure in deep strata. Except for the promotion of the thermal hydrocarbon generation within organic-rich source rocks, the global research on the influences of deep fluids, and the thermal energy associated with such fluids, on the process of hydrocarbon accumulation in sedimentary basins remains weak.

(4) Hydrocarbon accumulation process simulation and its combination with modern information technology. Complex superimposed basins are widely developed around the world. Multi-phase tectonic movements lead to multiple sets of source-reservoir-cap rock assemblages, multi-cycle accumulation, and multi-phase adjustments and transformations. In turn, these characteristics lead to the formation and distribution of complex petroleum resources involving long-distance migration, scale transformation, phase variation, and component destruction. It is, therefore, difficult to explore petroleum resources in superimposed basins. However, the combination of existing dataset with modern information technology and artificial intelligence techniques, such as machine and deep learning offer potential to improve exploration success in such systems. Such systems facilitate the analysis of petroleum reservoirs transformed by tectonic movements, petroleum reser-

voirs influenced by deep hydrothermal fluid, high-temperature cracking petroleum reservoirs, biological oxidation degradation of petroleum reservoirs, and petroleum reservoirs isolated by high-pressure and low-temperature and/or other special environmental conditions, to mention just a few of the complexities to be resolved. A required future development direction is to more widely apply intelligent systems to analyze and further evaluate the massive amount of historical data accumulated by oil and gas drilling extending over more than 100 years to achieve quantitative, automated and intelligent hydrocarbon accumulation and distribution prediction and evaluation systems.

4. Conclusions

As the "Action Plan for Carbon Peaking by 2030" issued by the State Council of China conveys, the objective in terms of carbon reduction and development, does not promote the short-term reduction in petroleum exploration and development, as the petroleum industry still requires further development to meet short-term demand for energy. However, future development direction of petroleum exploration and exploitation work need to change and adapt to meet the goals of "carbon peaking and carbon neutrality". The reports presented and discussed at the 8th ISHAMPRE reflect the international academic frontiers and highlight the petroleum exploration associated with achieving such goals.

Conflict of interest

The author declares no competing interest.

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