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Editorial

Recent advances on shale oil and gas exploration and development technologies

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Abstract:
In the face of the complex global energy transition, the development of unconventional oil and gas resources, such as oil shale, shale oil, and shale gas, encounters challenges related to carbon neutrality, technological complexities, and costs. However, the world's strained energy landscape and the fact that the new energy industry has yet to take shape also present rich opportunities for the development of these resources. Against this background, a conference platform was established at Jilin University for facilitating scholarly exchange and discussion on the exploration and development technologies of shale oil and gas. The 5th International Symposium on Shale Oil and Gas Exploration and Development Technologies was successfully held in Changchun from November 10 to 12, 2023. The symposium attracted over 210 experts and scholars from more than 59 institutions worldwide, representing the field of shale oil and gas exploration, development, and utilization. Participating delegates shared their accomplishments in the realm of shale oil and gas exploration and development technologies, engaging in profound discussions and fruitful exchanges on these subjects.

1. Introduction

With the rapid development of the global economy, human demand for energy is constantly increasing. Energy shortage has become an important issue that restricts the sustainable development of society. For a long time, oil and natural gas resources have dominated global energy consumption (Xu et al., 2022; BP, 2023; EIA, 2023; Sun et al., 2023). Vigorously developing oil and gas resources is the main means for major energy countries in the world to ensure their energy security. In addition, they are also actively exploring and developing unconventional oil and gas resources such as shale oil and gas (Zhao et al., 2020a, 2023; Zhang et al., 2021; Cai et al., 2022).

Shale oil and gas resources have the characteristics of abundant reserves and wide distribution, which are even expected to become an important replacement resource for conventional oil and gas with the rapid development of horizontal drilling and fracturing technologies (Gao et al., 2020; Hu et al., 2020; Jin et al., 2021). However, the development of shale oil and gas also faces a series of challenges, including high technical difficulty, high costs and the impact of the complex global energy transformation trend (Zhao et al., 2020b; Wang et al., 2021; Lei et al., 2023). Therefore, scientists from all over the world must strengthen cooperation, jointly research and solve these common problems, and promote the sustainable development of shale oil and gas resource exploitation (Kang et al., 2020; Taheri-Shakib and Kantzas, 2021).

With the theme of "Challenges and Opportunities for Shale Oil and Gas Development under the Background of the Energy Revolution", the 5th International Symposium on Shale Oil

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and Gas Exploration and Development was held successfully on November 10 to 12, 2023. This symposium provides a platform for experts and scholars in the field of shale oil and gas to exchange and cooperate, aiming to fully discuss cutting-edge theoretical research, hot technology research, and development strategy deployment in the field of shale oil and gas, as well as accelerate the exploration and development of shale oil and gas resources. The previous four international symposiums on oil shale exploration and development have been held in 2011, 2014, 2018 and 2020, and have become important academic activities in the field of shale oil and gas.

This symposium featured a total of 52 presentations, including 4 keynotes and 16 invited speeches. More than 210 representatives from 59 domestic and international institutions, including China, the United Kingdom, Israel, Jordan, Estonia and Pakistan, attended this symposium. The participants shared the latest research findings on shale oil and gas exploration and development technologies in the symposium and engaged in in-depth discussions and exchanges in related fields, further enhancing the understanding of the prospects and challenges of shale oil and gas development. The research topics covered in this symposium are briefly described as follows.

2. Geological theory and resource potential

Wenzhi Zhao, from the PetroChina Research Institute of Petroleum Exploration and Development, delivered a speech entitled "Concept and significance of component flow in continental shale oil". He pointed out that there are significant differences between the "retention enrichment" of shale oil and the "migration accumulation" of conventional oil. The characteristics of "component flow" in shale oil not only depend on the composition of trapped hydrocarbons and the energy field of the formation but are also closely related to the development methods and production systems. It is crucial to uncover the "retention enrichment" and "component flow" properties of shale oil as early as possible to facilitate the large-scale and advantageous development of shale oil resources.

Zhou Lihong, from Dagang Oilfield, presented a talk titled "Theoretical understanding of continental shale oil formation and reservoir and beneficial development practice". He used the Huanghua Depression in Bohai Bay Basin as a case study to present his theoretical and technical research on shale oil enrichment in continental basins. Dagang Oilfield has taken the lead in completing the overall anatomy of continental laminated texture shale oil in China and has achieved beneficial development after the four stages of straight well discovery, horizontal well breakthrough, capacity evaluation and benefit development. Nowadays, Dagang Oilfield has formulated a million-ton production plan, contributing to the goals of China's shale oil revolution.

Jun Jia, from the Oil and Gas Resources Strategic Research Center, Ministry of Natural Resources (China), gave a presentation titled "Progress in shale oil resource evaluation in the 14th Five-Year Plan". She introduced the national oil and gas resource evaluation project in the 14th Five-Year Plan from China's Ministry of Natural Resources. The evaluation work on shale oil was comprehensively explained from various perspectives, including the concept, resource sequence, starting conditions, classification schemes, evaluation methods and parameters. She also pointed out that, China had accumulated 1.41 billion tons of proven shale oil geological reserves and 4.24 billion tons of predicted controlled reserves (Level 3, 5.65 billion tons).

Colin E. Snape, from the University of Nottingham, delivered a speech titled "Shale gas reserve estimation using laboratory pyrolysis: A UK case study". He first introduced the rationale behind using high-pressure water pyrolysis to simulate shale gas generation and assess reserves. Then he presented the estimated gas in place for the whole UK Bowland shale based on research findings. Finally, he discussed their latest research progress in modeling methane adsorption for wet kerogens.

Rong Liu, from Jilin University, gave a talk titled "Organic matter enrichment and bioenvironmental effects in paleolake of oil shale-bearing series in China". She highlighted the strong correlation between geological events and the enrichment of organic matter and provided a comprehensive analysis of the coupling mechanism between these events and organic matter enrichment. Additionally, she proposed that conducting interdisciplinary research combining microbiology and geoscience would be a crucial approach to uncover the intricate relationship between organic matter enrichment and geological events.

Zhenxue Jiang, from the China University of Petroleum (Beijing), delivered a presentation titled "Main controlling factors of shale oil enrichment and oil mobility evaluation in Fengcheng Formation of Mahu Sag". He introduced the pore-fracture development characteristics of the shale reservoir of Fengcheng Formation in Mahu Sag and the occurrence characteristics of shale oil based on lithofacies division, clarified the control effect of shale oil enrichment from the perspective of source and reservoir, and comprehensively analyzed the main controlling factors of shale oil enrichment and evaluated the mobility of shale oil.

Yinbo Xu, from the China Geological Survey, gave a talk titled "Progress of geological survey of oil shale in key areas". He presented the overall work of the China Geological Survey in the field of oil shale in recent years. He specifically introduced the geological survey achievements and progress in the Songliao Basin, Fushun Basin, Qaidam Basin, and Santanghu Basin. Furthermore, he provided detailed insights into the new advancements and understandings achieved in nationwide dynamic tracking of oil shale, experimental techniques for oil shale electrical detection and the metallogenic theory of oil shale.

Zhujiang Liu, from the Physical Exploration Research Institute, Exploration Branch, Sinopec, delivered a lecture titled "Progresses in evaluation on deep shale gas exploration in Wufeng-Longmaxi Formation in the south-eastern part of Sichuan Province". He introduced that Sinopec discovered the first medium-deep to deep shale gas field, Qijiang Shale Gas Field, in the complex area of the southeast Sichuan basin margin on Nov. 18, 2022. It was a typical self-generating

and self-storing shale gas field that exhibited characteristics of integrated source and reservoir, large-scale layered distribution and overall gas saturation. Qijiang Shale Gas Field was a medium deep-deep, high-pressure and high-quality natural gas reservoir. Currently, it has submitted 145.968 billion m^3 of proven geological reserves.

Zhaolin Qi, from Qinghai University, delivered a talk titled "Characteristics and paleoenvironmental analysis of Cenozoic oil shale of the Gongjue formation in Nangqian basin, Qinghai province". He presented the geological survey findings on Nangqian Basin oil shale in Qinghai, China. Firstly, the Paleoproterozoic Basin had a widespread distribution of oil shale. Secondly, although the organic evolution degree was not high, the oil yield was sufficient for industrial development, and it contained a significant amount of non-hydrocarbons. Lastly, the paleoenvironment of the Gongjue Formation experienced a brief period of climatic cooling during oil shale deposition.

3. Geophysical survey methods and identification techniques

Hongwei Li, from the PetroChina Research Institute of Petroleum Exploration and Development, delivered a talk titled "Detection of shale gas sweet spots in Duvernay Shale based on data clustering and in situ imaging techniques". He conducted a correlation analysis between shale gas production and various factors, including effective thickness, reservoir properties and total organic carbon content in different well areas. Through cluster analysis of well logging and seismic data, he identified distinct well logging anomalies and seismic responses that distinguish the "sweet spots" of shale gas, which differ from the background data. Based on this, He employed multidimensional data clustering and in-situ imaging techniques to redefine the distribution of shale gas sweet spots, providing valuable guidance for the efficient exploitation of shale gas in the Duvernay Formation.

Qamar Yasin, from Northeast Petroleum University, presented a lecture titled "An improved convolutional architecture for automatic pore structure analysis in organic-rich shale using FIB-SEM". He proposed a method to transform shale CT images accurately and quickly into core images containing multiple mineral components using a KiU-Net model. The CT images of shale samples were matched with the corresponding QEMSCAN images, and a KiU-Net model was trained to achieve automatic segmentation of CT images.

Ruilong Jia, from Jilin University, delivered a presentation titled "Study on the relationship between complex resistivity and dielectric constant with saturation in rich organic shale". He demonstrated a correlation between the difference and ratio of low-frequency and high-frequency resistivity and rock saturation. Graphical interpretation could be used to qualitatively determine the level of water saturation in rocks. However, the quantitative description remained challenging due to the uncertainty in frequency selection. Furthermore, the relative dielectric constant of rocks was influenced by the distribution of rock components. As water saturation increased, the relative dielectric constant would also increase.

Baiqiang Tang, from Jilin University, gave a presentation titled "Logging identification of lithology in fine-grained sedimentary rocks: A hybrid model combining optimization algorithms and machine learning". He proposed a sparrow search algorithm (optimization algorithm) that introduced firefly perturbation. Taking the Qingshankou stratigraphic section in the Songliao Basin as the target layer, combined with a hybrid kernel extreme learning machine, the algorithm achieved good comprehensive prediction performance in blind wells, with an accuracy rate of 80.39%, showing good applicability.

4. Pyrolysis mechanism and surface retorting technology

Oliver Järvik, from Tallinn University of Technology, delivered a presentation titled "Gaseous emissions related to the solid heat carrier technologies in the Estonian shale oil industry in the past, present, and future". He pointed out that Estonia predominantly utilized various solid heat carrier technologies for shale oil production. However, there is significant variation in the performance of these technologies regarding gaseous emissions. Despite the advancements made in reducing gaseous pollutants from shale oil production, the shale oil industry now faces the challenge of significantly reducing CO_2 emissions as well. CO_2 capture and feedstock mix were considered two potential future scenarios for the shale oil industry.

Omar S. Al-Ayed, from Al-Balqa Applied University, presented a talk titled "Shale oils, heteroatoms, distillation curves, similarities and differences with crude oil". He demonstrated the correlation between the true boiling curve data of crude oil and its vacuum conditions data. Therefore, it was possible to derive the atmospheric distillation curve based on the results of the vacuum distillation experiment. He also established a correction factor modification to address the issue of poor fit of the Q parameter in predicting the temperatures at atmospheric conditions from the subatmospheric data.

Shuang Liu, from the Engineering Technology Research Center of Fushun Mining Group Co, delivered a talk titled "Research and application of high efficiency transformation and utilization technology for oil shale separation". He introduced a series of key technologies successfully developed by his company, including the uniform retorting technology based on continuous screening of block oil shale, the cross-flow retorting technology for small particles oil shale, co-retorting technology for low-grade oil shale and organic solid waste, and the deep recovery and gradient utilization technology for full-grade residual energy. These technologies could also be promoted and applied to unconventional energy resources such as oil sands and coal gangue.

Xinmin Wang, from Northwest Electric Power University, gave a presentation titled "Study on thermal evolution process of Fushun oil shale by molecular simulation and experimental". He proposed a two-dimensional molecular structure model for Fushun kerogen based on experiments and molecular simulations. In his work, a three-dimensional molecular model of kerogen was constructed, optimized, and validated using evaluation methods such as density and chemical bond concentration. Finally, he revealed the pyrolysis mechanism

of oil shale from a microscopic molecular perspective through molecular dynamics simulations.

Haipeng Liu, from the State Power Investment Shandong Electric Power Engineering Consulting Institute, gave a talk titled "Characteristics of CO_2 and metal catalysts synergistically catalyzed pyrolysis of oil shale to produce rich light fuel oil". In his talk, he presented the influence of N_2/CO_2 atmosphere and metal catalysts on the composition evolution of organic products during Huadian oil shale pyrolysis. The results demonstrated the pivotal role of transition metal cations in facilitating the secondary cracking of shale oil. Moreover, the oxygen radicals generated from CO_2 efficiently reacted with high molecular weight organics during the cracking process, thereby enhancing their conversion into lighter fuels.

Tianbao Liu, from Northeast Petroleum University, delivered a presentation entitled "Catalytic pyrolysis of oil shale kerogen and product control". He synthesized a NiFe-LDH catalyst that could promote the cleavage of C-C, C-H, and O-H bonds in organic compounds. He conducted a systematic analysis of the influence of different metal ratios, surface structures and morphologies on the catalytic pyrolysis behavior of kerogen, and further revealed the mechanism of action of the catalyst throughout the three stages of kerogen pyrolysis. The results showed that this catalyst effectively lowered the pyrolysis temperature of oil shale.

Jiaxue Zou, from Northeast Petroleum University, delivered a presentation titled "Response of nano-pore structure of low-maturity shale to super-heated steam pyrolysis". She conducted a comprehensive study on the microstructural evolution and nanoscale pore structure evolution mechanisms of low-maturity shale during superheated steam pyrolysis. She revealed the differential response of various organic matter pores to temperature and comprehensively analyzed the evolution characteristics of low-maturity shale pores under the combined effects of organic matter pyrolysis, dissolution and decomposition of inorganic minerals, and transformation of clay minerals.

5. Key technologies for in-situ exploitation

Dong Yang, from the Taiyuan University of Technology, delivered a talk entitled "Study on fracture evolution and permeability response during oil shale exploitation by in-situ convection heating". He introduced that oil shale exhibited strong anisotropic characteristics in terms of pore and fracture distribution and evolution during pyrolysis. The permeability in the parallel bedding direction was significantly enhanced due to the development of fractures, while the permeability in the vertical bedding direction should gradually increase through the connectivity of larger pores. The anisotropic nature of the pore-fracture system and permeability in oil shale facilitated the improvement of convective heating efficiency and prevented heat from spreading into areas beyond the targeted shale layer.

Qiang Li, from Jilin University, presented a speech entitled "Pilot project and key technology of oil shale in-situ conversion and exploitation by Jilin University". He introduced the new oil shale in-situ exploitation technologies developed by Jilin University and the two field pilots. These pilots demonstrated a technological leap from shallow to deep, from near to far, and from easy to difficult, thereby initially verifying the feasibility of industrial-scale exploitation of oil shale through in-situ exploitation. He asserts that enhancing heat injection efficiency, seepage replacement efficiency and technical economy were the key directions for future development of in-situ exploitation technology.

Dimitry Dveryrin, from the Asia Group Corporation Ltd., gave a talk titled "TCSHOP Technology thermo-chemical shale and heavy oil production technology process enhancement – laboratory investigation". He introduced that changes in groundwater flow direction could impact the productivity of shale oil, which would be enhanced through hydraulic control processes. The efficiency of bidirectional flow processes was higher than that of unidirectional flow processes, with the configuration of a six-point well network in the process control achieving the highest extraction efficiency (88%). For on-site experiments, he recommended the use of automatic control flow direction schemes based on real-time pressure and temperature measurements.

Yulin Ma, from the Liaoning University of Engineering and Technology, gave a lecture titled "Multi-field coupled pyrolysis simulation of oil shale reservoir under microwave radiation". He showed the regulation of temperature, seepage and displacement changes in oil shale reservoirs during microwave heating. The results demonstrated that an appropriate heating power could not only heat the reservoir efficiently but also protect the heating wellhead and revealed the significant impact of microwave heating on the porosity and permeability of oil shale reservoirs which could deepen the understanding of the thermal effects of microwave radiation on oil shale.

Hongying Yuan, from Tianjin Urban Construction University, delivered a presentation titled "Construction of ecological environment evaluation system for in-situ exploitation of oil shale". She proposed a three-category, ten-indicator system for evaluating the ecological environment of in-situ exploitation of oil shale focused on the characteristics of ecological impacts caused by in-situ exploitation of oil shale. Then she evaluated a demonstration area for oil shale, which provided preliminary validation of the practicality and feasibility of the model. Moreover, He emphasized the importance of accounting for carbon emissions throughout the entire lifecycle of oil shale development, from site development to oil refining and utilization.

Shengyuan Song, from Jilin University, gave a report titled "Research on the spatiotemporal evolution of surface deformation during the entire process of oil shale in-situ mining". Taking the Fuyu oil shale in-situ pyrolysis pilot test base as an example, he introduced the characteristics of change in pore structure, thermophysical and mechanical properties of the oil shale formation, presented the heat-fluid-solid coupling model for the whole formation and the entire process of the pyrolysis base. Finally, he uncovered the mechanism of subsurface pyrolysis and surface synergistic deformation in the oil shale in-situ exploitation area.

6. Advanced and intelligent drilling technologies

Xianzhi Song, from the China University of Petroleum (Beijing), delivered a speech entitled "Discussion on artificial intelligent technology in drilling". He developed an intelligent drilling technology that combines well drilling with artificial intelligence. This technology enabled the intelligent identification of geological conditions and the location of oil and gas reservoirs, intelligent guided drilling, high-quality drilling encounters, automatic parameter optimization, closed-loop risk control, and intelligent decision-making. He believed that future intelligent development should transition from perceptual intelligence to cognitive intelligence and decision-making intelligence, achieving the collaborative evolution of small-scale models in specific scenarios to large-scale or small-scale models in the industry.

Zhiyong Chang, from Jilin University, gave a talk entitled "New technology of oil detection and non-point source pollution assessment based on bionic olfaction". He developed a biomimetic electronic nose that could rapidly detect trace gas compositions under special working conditions. Through the optimization of the biomimetic chamber's design and structure, the detection accuracy and recognition ability of the technique was improved. It has been successfully utilized for real-time monitoring of oil shale pyrolysis processes and assessment of petroleum hydrocarbon surface source pollutants in soil. He believed that bionic olfaction could be expanded to detect multiple gas sources in complex conditions, including oil and gas exploration, environmental safety, and deep-sea polar scientific expeditions.

Feifei Zhang, from Changjiang University, delivered a speech titled "Data-driven and physics coupled drilling model and its application in predrilling design-RT monitoring- post drilling analysis". He introduced a multi-source, multi-mode drilling data fusion method developed by his team. Additionally, he proposed a drilling risk early detection and anomaly diagnosis method based on data mining methods and decision-making theories. Then, he demonstrated a life cycle drilling analysis platform, which covered pre-drilling design, real-time monitoring, and post-drilling evaluation. The platform was beneficial for the advancement of drilling digitalization and intelligent drilling.

Li Zhang, from the PetroChina Research Institute of Petroleum Exploration and Development, delivered a presentation titled "Analysis of the current research status of magnetic guided drilling technology". He analyzed the specific applications in various scenarios such as coalbed methane U-type wells, rescue wells, and heavy oil thermal recovery. He proposed a novel approach that combines the dual-horizontal well magnetic guidance drilling technology with long-distance magnetic guidance drilling technology to exploit shale oil in situ. He firmly believed that the future of magnetic guidance drilling technology lies in expanding the range and enhancing the accuracy of wellbore trajectory.

Yan Zhao, from Jilin University, gave a presentation titled "Research on precise ignition and intelligent temperature control technology of continuous cable tube for underground in-situ gasification of coal seams". He developed a snake-like continuous pipe storage system which could be precisely controlled, providing excellent conditions for the stable transmission of electricity, signals, gas-liquid-solid three-phase flow, and other channels from the surface to underground without obstacles. This system effectively addressed the technical challenges of mutual jamming, biting, locking, and poor stability during the dynamic-static transition of existing continuous pipe reels. It would provide equipment support for underground coal gasification, mining emergency rescue, and continuous pipe drilling technology.

Yinlong Ma, from Jilin University, presented a talk entitled "Research on the frontier technology of continuous coring for directional drilling". Aiming at the technical problems of exploration such as low rates of rock (ore) coring, high single-hole investment and limited access to geological information, He proposed a precise directional drilling and continuous coring technology with high-precision, low-cost, high-efficiency which could overcome the technical bottleneck of incompatibility between directional drilling and coring, realize the precise adjustment of drilling track and accurate access to the underground three-dimensional space of the geological rock core.

Shengjie Lin, from the CNPC Engineering Technology RandD Company Limited, gave a presentation entitled "The research progress of horizontal well with small spacing drilling technology in shale oil in-situ development". He believed that the traditional magnetic guidance drilling technology could not meet the small well distance density drilling and the "vertical well + directional well + horizontal well" cluster drilling requirements of medium-low maturity shale oil. However, the borehole spacing error obtained by "U" needle magnetic ranging and double-horizontal well magnetic ranging technology is less than 5% within the range of 5m well spacing, which could provide technical ideas for in-situ development of shale oil and had guiding significance.

7. Borehole wall stability and stimulation techniques

Jianzheng Su, from the Sinopec Petroleum Exploration and Production Research Institute, delivered a presentation entitled "Fracture research and production enhancement direction in shale oil reservoirs". He introduced the essential role of natural fracture and artificial fracture systems through intensive hydraulic fracturing in the flow of shale oil. He proposed a CO_2 pre-fracturing technique for continental shale oil, which could enhance the mobility and complexity of shale oil flow. This method increased pump pressure and proppant placement frequency, affecting the effectiveness of fracturing, but it reduced the gap between fracturing fluid infiltration and absorption, thereby improving reservoir efficiency.

Jingping Liu, from the China University of Petroleum (East China), delivered a speech entitled "Research on high-performance shale gas water-based drilling fluids". He developed a nano-hydrophobic inhibitor that could form a biomimetic micro-nano composite structure on the rock surface, altering the wettability of shale and effectively inhibiting

its hydration. Additionally, he designed a polymer nano-plugging agent with a core-shell structure, which could enhance the efficiency of drilling fluid in plugging nanoscale pores and significantly reduce the pressure transmission effect of drilling fluid, thereby stabilizing the wellbore. The field tests demonstrated the effectiveness of the drilling fluid in solving challenges related to wellbore instability and well leakage, making it highly significant for the efficient development of shale gas.

Lili Yang, from the China University of Petroleum (Beijing), delivered a presentation entitled "New drilling fluids technologies for unconventional oil and gas reservoirs". She developed a biomimetic solid wall agent that could form a dense biomimetic film on the surface of hydrate cores. This agent effectively prevented the invasion of drilling fluids, enhanced the adhesion of the core surface, and improved the compressive strength of the core. Additionally, she constructed a self-healing gel material for plugging drilling fluid, which exhibited excellent sealing performance and sand consolidation effects. Furthermore, she invented an efficiency enhancer for drilling fluids, achieving the goal of "dual wettability" on the near-wellbore rock surface that successfully addressed issues such as wellbore instability and reservoir damage.

Cheng Zhai, from the China University of Mining and Technology, gave a speech entitled "Strategic conception and research progress of methane in-situ deflagration fracturing technology in shale reservoirs". He introduced an innovative in-situ methane deflagration fracturing technology for shale reservoirs. This technology utilized the in-situ desorbed methane gas and the injected combustion-assisting agents to cooperatively deflagrate and generate high-temperature and high-pressure gas to impact and fracture the shale reservoir, creating 3D fracture networks to provide efficient migration pathways for shale gas. It might be a forward-looking and revolutionary technology that would help achieve innovative breakthroughs in China's shale gas development technologies.

Yu Zhao, from Guizhou University, delivered a presentation entitled "Discussion on dominant factors and crack evolution issues during hydraulic fracturing". He shared his research and insights in the presentation, covering the dominant factors in hydraulic fracture propagation, hydraulic fracturing simulation considering heterogeneous fluid pressure, the intersection between hydraulic fracturing and natural fractures, and the formation of complex fracture networks. These research findings and insights not only enhanced the completeness and richness of the presentation but also provided theoretical guidance for shale hydraulic fracturing studies.

Jianchao Cai, from the China University of Petroleum (Beijing), presented a lecture entitled "Mechanism and evaluation of micro-nano scale shale pore structure evolution induced by acid treatment". He characterized the evolution patterns of shale micro-nano scale pore structures by combining micro-CT scanning and nitrogen adsorption methods. Based on fractal theory, he comprehensively evaluated the evolution characteristics of shale pore structures by considering parameters such as fractal dimension, pore connectivity, and pore throat size.

Haizhu Wang, from the China University of Petroleum (Beijing), delivered a talk entitled "Study on fracture initiation mechanism of supercritical CO_2 fracturing in shale oil reservoirs". He introduced the mechanisms of fracture initiation and propagation in shale oil reservoirs under the action of SC-CO_2 fracturing through the results from laboratory hydraulic fracturing experiments and finite discrete element simulations. The results revealed that SC-CO_2 could significantly reduce the fracturing pressure of shale reservoirs and enhance the complexity of the fracture network. However, the long-term effects on the reservoir due to the reaction of SC-CO_2 with water formation, resulting in acidic fluids, still require further investigation.

Heyuan Wang, from Northeast Petroleum University, gave a talk entitled "Research on shale oil borehole collapse mechanism". In his presentation, he proposed an experimental method to simulate drilling fluid intrusion into shale, replacing the overall intrusion with end-face intrusion, and replacing the overall pressurization with the two-way pressure of circumferential pressure and injection pressure. This method was more in line with the actual conditions of the drilling fluid intrusion around the wells and could be used to reveal the mechanism of the collapsing and destabilizing of the shale oil borehole.

8. Development path and policy analysis

Youhong Sun, from the China University of Geosciences (Beijing), delivered a speech titled "Technical challenges and response strategies for in-situ exploitation of low-medium maturity shale oil". He introduced that the characteristics of continental low-medium maturity shale oil had similar properties to oil shale, requiring in-situ conversion technology for effective development. However, in-situ conversion technology still faced various technical challenges, including the development of small-sized, high-power, long-life and long-distance mineral-insulated electric heaters, electromagnetic ranging guidance technology for multi-lateral wells with small spacing, and efficient composite heating technology. Overcoming these technologies would enhance the efficiency of in-situ heating, reduce the cost, and development cycle of drilling and in-situ conversion.

Deqiang Sun, from the Institute of Science and Technology Strategy Consulting, Chinese Academy of Sciences, presented a talk entitled "Development status, problems and countermeasures of China's shale oil and gas revolution". He introduced the development process of shale oil and gas in China, emphasizing the need to strengthen the assessment, development, introduction and innovation of the key and disruptive technologies. He also highlighted the importance of formulating a long-term national energy security strategy. He proposed a development strategy and research measures for the technological innovation and governance system of shale oil, and emphasized that China should implement shale oil research programs tailored to its national conditions to promote the steady development of shale oil.

Jinfeng Ma, from Northwestern University, gave a lecture entitled "History, status and direction of development of geological storage of carbon dioxide". He sequentially introduced the origins of carbon capture and storage (CCS) projects, the classification of CCS projects, key issues in CO_2 capture,

the status of CCS projects, and the crucial scientific and technological challenges in CO_2 geological storage. He highlighted that the major challenges in CO_2 capture technology lie in the large-scale and low-energy consumption capture of low-concentration CO_2 flue gas. In terms of the future development direction of geological storage, he emphasized the importance of saline aquifer storage, followed by oil reservoirs and abandoned gas fields.

Kun Wang, from the China Petroleum National Institute of Excellence Engineers, gave a talk titled "New Opportunities for the Development of New Oil and Gas Resources under the Dual Carbon Strategy". He pointed out that China possesses substantial untapped oil and gas resources within its continental strata, including low-medium maturity shale oil and oil-rich coal that could be effectively exploited using in-situ conversion technologies. Considering China's current level of equipment and technology, it was anticipated that, through intensified scientific and technological research and improved production organization, large-scale development of these new oil and gas resources could be achieved by 2040. These resources were expected to become important strategic alternative resources for China's oil and gas industry.

Yang Gao, from the China National Petroleum Exploration and Development Research Institute, delivered a presentation titled "Progress of continental unconventional oil and gas exploration in China and prospects for future development". He introduced that, China had continuously innovated the understanding of the geological theory of continental shale oil and gas which gradually became important roles in ensuring the increase of oil and gas reserves and production. China's unconventional oil and gas resources were most abundant in the seven major oil and gas enriched basins, including Ordos, Bohai Bay, Junggar, and Sichuan. The exploration potential for shale gas was particularly promising in the deep layers of the Longmaxi Formation and the new stratigraphic series.

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Conflict of interest

The authors declare no competing interest.

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