

Perspective

Key issues and development direction of petroleum geology research on source rock strata in China

Jiarui Li, Zhi Yang^{✉*}, Songtao Wu, Songqi Pan

Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, P. R. China

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Abstract:

After more than 20 years of technological advancements, the novel field of oil and gas production from source rock strata, which comprise tight and shale oil and gas reservoirs, has become the major contributor to the increase in unconventional oil and gas reserves in China. Accordingly, this field has gradually entered a new stage of revolutionary development. The oil and gas production in China from source rock strata will achieve sustainable development in the future. Different types of source rock strata present distinct challenges and require diverse development paths. Based on the geological conditions of source rock strata in China, this study focuses on identifying the “sweet areas” among hydrocarbon accumulations. It specifically analyzes the key development issues of tight oil, tight gas, shale oil, shale gas, and coal-bed methane, while proposing potential solutions and identifying the possible directions for future development. This study aims to provide a reference for scientists concerned with the development of unconventional oil and gas reserves in China.

1. Introduction

Source rock strata can be used to obtain a continuous distribution of oil and gas resources that can be exploited industrially by using existing technologies, in which hydrocarbons are generated, retained, or gathered in the source rocks or in the tight reservoirs adjacent to the source rocks (Yang et al., 2019b, 2021). Oil and gas are derived from source rock strata using two types of resources: source rock reservoirs including shale oil, shale gas, and coal-bed methane (Yang et al., 2019a; Zou et al., 2019b), as well as tight oil and gas reservoirs adjacent to the source rocks (Yang et al., 2015; Sun et al., 2019). The overall strategic development of unconventional production of oil and gas in China is now being realized, with the utilization of source rock strata. Furthermore, the field of tight sandstone gas production has seen large-scale development (Dai et al., 2012; Sun et al., 2019). The need for an accelerated development of shale gas and tight oil reservoirs has garnered significant attention (Hao et al., 2013; Chen et al., 2015; Yang et al., 2015; Jin et al., 2016; Ma et al., 2018; Jiao et al., 2020; Xu et al., 2020; Horsfield et al., 2021; Venieri et

al., 2021; Zou et al., 2021). Meanwhile, shale oil production has shown potential to allow further exploration (Du et al., 2019; Yang et al., 2019c; Hu et al., 2020; Zhao et al., 2020; Zou et al., 2020), and manufacturing of coal-bed methane has demonstrated stable development (Sun et al., 2021). Overall, oil and gas derived from source rock strata have become major contributors for the increase in unconventional oil and gas reserves in China (Yang et al., 2021).

2. Petroleum geology characteristics of source rock strata in China

The core of hydrocarbon accumulation in source rock strata is the source rock. Within the strata, a large amount of oil and gas resources are gathered in the source rocks and in the tight reservoirs adjacent to the source rocks. The onshore source rock strata in China are characterized by varied sedimentary environments and complex lithofacies, ranging from the Mesoproterozoic to the Quaternary. The hydrocarbon accumulation distribution in the source rock strata can be roughly divided into Cenozoic, Cretaceous, Jurassic-Triassic, Upper

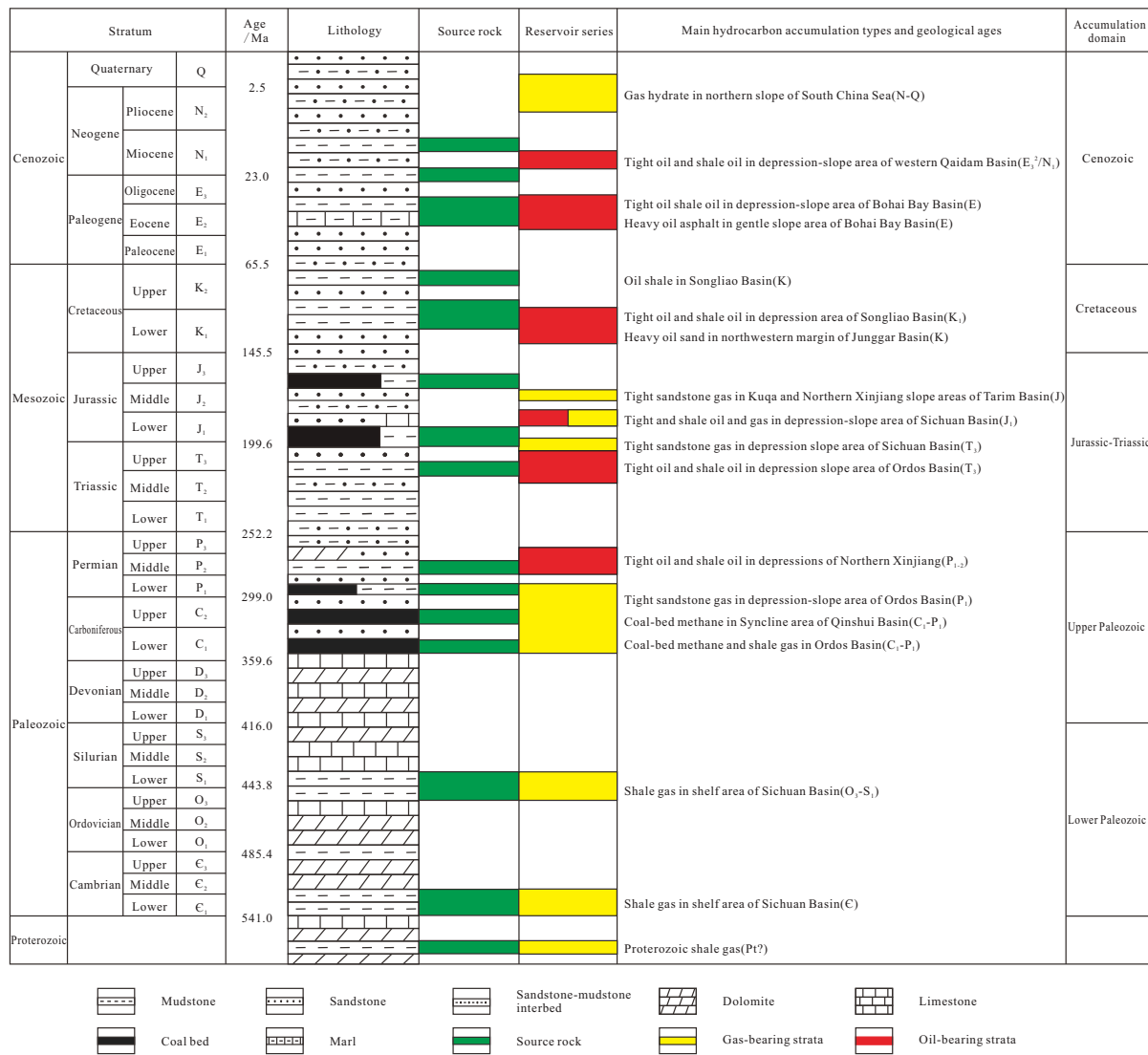


Fig. 1. Comprehensive histogram of unconventional oil and gas resources in China (Yang et al., 2021).

Paleozoic, and Lower Paleozoic accumulation domains (Fig. 1) (Yang et al., 2021). Among these, the Cenozoic is represented by tight oil and shale oil in the Paleogene strata of the Bohai Bay and Qaidam basins. The Cretaceous is represented by tight oil and shale oil in the Songliao Basin. The Triassic-Jurassic is represented by tight oil and shale oil in the Ordos Basin, tight oil and shale oil in the Sichuan Basin, and tight sandstone gas in the Tarim Basin. The Upper Paleozoic is represented by Carboniferous-Permian tight sandstone gas and coal-bed methane in the Ordos Basin and tight oil and shale oil in the Junggar Basin. The Lower Paleozoic is represented by Wufeng-Longmaxi Formation shale gas in the Sichuan Basin.

The study of oil and gas deposits in source rock strata in China is a new area of research in petroleum geology, which studies the types, occurrence mechanisms, enrichment laws, distribution characteristics, production mechanisms, assessment methodologies, key technologies, and development strategies of oil and gas resources in China's onshore source rock strata (Yang et al., 2021). The oil and gas derived from

source rock strata are distributed continuously in the center and the slope area of the basin over a large range. Furthermore, the source rocks and reservoirs coexist without obvious trap boundaries, which breaks through the concept of conventional oil and gas reservoirs; consequently, the objective of the research shifts from "trap and reservoir" to "reservoir sweet area" (Zou et al., 2019b; Yang et al., 2021). The core focus in the research on the oil and gas geology of source rock strata is to study and evaluate the sweet area (section) of hydrocarbon accumulations in the source rock strata; that is, on the plane (section) of the source rock strata, artificial stimulations are induced throughout by using existing technologies to produce a favorable zone (section) that comprises industrial oil and gas deposits (Yang et al., 2021). The identification of the "sweet area" (section) is carried out using the product of the six-property relationship, which includes the source rock, reservoir, oil-bearing, liquidity, fracture, and economy. The source rock property represents the hydrocarbon generation potential and spatial distribution of high-quality source rocks;

it is used to find organic-rich source rocks. The reservoir property represents the formation and distribution of lithology and lithofacies, reservoir capacity, and connectivity of pore throat-fracture network systems in tight reservoirs, with the aim of finding effective reservoir development areas and screening sweet reservoir are as that exhibit relatively good porosity and permeability (Ijeje et al., 2019; Cai et al., 2020; Liang et al., 2021). The oil-bearing property represents the occurrence state and filling degree of oil and gas in tight reservoirs, with the aim of optimizing reservoirs with good oiliness. The fluidity property represents the formation energy, fluid composition, oil and gas quality, and the seepage-diffusion-adsorption characteristics of tight reservoirs, with the aim of determining oil and gas reservoirs that exhibit strong mobility and can be easily exploited. The fracture property represents natural fractures, artificial fractures (stimulated throughout the network), and the stress characteristics of tight reservoirs, with the aim of optimizing high-brittleness reservoirs that facilitate large-scale fracturing. Finally, the economy property represents the real potential of oil and gas resources, low-cost development paths, and economic and social benefits; it aims to improve the efficiency of exploration and development under the premise of ensuring sustained production.

3. Key issues in petroleum geology of source rock strata in China

Currently, the development of oil and gas production from onshore source rock strata in China faces many issues and challenges, such as lack of theoretical understanding, technological research and development, and cost control; these factors seriously restrict the large-scale utilization and effective exploitation of source rock strata as oil and gas resources.

Tight oil

- The lithology of an onshore tight reservoir is complex and difficult to predict, while the stability and continuity of the reservoir distribution are poor.
- The degree of thermal evolution of onshore source rocks is low, oil viscosity is generally large, and oil fluidity in the reservoir is poor.
- The target layer is mainly under medium or low pressure, and generally requires energy storage and pressurization; therefore, it is difficult to develop this layer effectively.
- The degree of geology-engineering integration is low, while the applicability of key technologies still needs to be improved and the development cost is still high.

Shale oil

- The onshore shale strata are mainly in the medium and low maturity windows because of the low thermal evolution degree, low hydrocarbon generation conversion of organic matter under natural conditions, high oil viscosity, and low movable oil proportion.
- The porosity and permeability of shale reservoirs are extremely low. Inorganic pores in clay minerals function as the main reservoir storage; however, organic pores are generally underdeveloped, with poor storage and connectivity.
- The natural fractures in shale reservoirs are relatively

low, and the content of plastic clay minerals is high; this renders the creation of artificial fractures difficult.

- The underground processing of shale oil is a physical and chemical process, in which the “horizontal well electric heating upgrading” technology is used to constantly heat the organic-rich shale intervals at buried depths ranging from 300 m to 3000 m, thereby converting various types of organic matter into light fractions (Zhao et al., 2020). At present, there are still some uncertainties in the promotion of an underground in situ conversion processing technology that uses heating.

Tight sandstone gas

- The exploration targets of continental and transitional facies are deeper and more complex, and the natural gas accumulation patterns are changeable; therefore, it is difficult to find new sources of tight sandstone gas.
- It is difficult to optimize well patterns and design horizontal well trajectories because of the strong heterogeneity of gas-bearing sand body distribution and the significant number of uncertainties during reservoir prediction between wells.
- The percolation law of tight sandstone gas areas with different water cuts is complex, and the reserve production capacity is very low.
- Key technologies, such as reservoir reconstruction, need to be strengthened for adapting to the characteristics of low-grade tight sandstone gas areas and improving the single-well production.

Shale gas

- There are still many unknown aspects with regard to the basic geological understanding of organic-rich shale distribution, reservoir mechanisms, and shale gas enrichment laws of onshore and marine-onshore transitional facies.
- Except for the shale gas of the Wufeng-Longmaxi Formation in the Sichuan Basin and its surrounding areas, the multi-layer marine shale of the Cambrian and Carboniferous has not been fully discovered.
- Research on deep marine shale fracturing, atmospheric shale low-cost fracturing, fault and fracture prediction, big data, artificial intelligence, and other technologies still need to be strengthened, and a new three-dimensional development model of an artificially stimulated fracture present throughout the gas reservoir still needs further exploration and innovation.

Coal-bed methane

- Insufficient preparations for medium and low rank coal-bed methane resource reserve areas.
- The production of single wells is low, while their inefficient development is a significant issue.
- The geological conditions are complex, while coal-bed methane exploration and development technologies are difficult to replicate.
- Underground coal gasification refers to the process of producing CH₄, H₂, and other combustible gases through in situ controlled combustion of coal in the strata with an appropriate engineering technology (Zou et al., 2019a). At present, there are still some uncertainties with regard

reservoir type		oil and gas accumulation profile	theoretical understanding	key technology	strategic positioning	representative example
oil shale			The whole contains organic matter. The organic-rich lithofacies of deep lake and shallow lake in depression control the distribution of oil shale with high oil content.	Surface distillation and heating in-situ conversion.	Important resources of oil shale	Huadian, Dunmi Basin
shale oil	medium and low maturity		The thick and large area organic-rich shale contains organic matter and hydrocarbons as a whole.	Horizontal well electric heating and other underground in-situ conversion technology.	Strategic replacement resources of shale oil	Chang 7 Member of Ordos Basin Nenjiang Formation of Songliao Basin
	medium and high maturity		Organic-rich sections are oil-bearing and distributed continuously. Rich and high yield in fracture-development section of lamina.	Horizontal well cutting volume fracturing and large platform development.	Important resources of shale oil now	Qingyi Member of Songliao Basin
tight oil	medium and high pressure		Organic-rich shale layers are oil-bearing and distributed continuously.	Horizontal well complex fracture network fracturing platform development.	Important substitute resources for tight oil	Permian in Junggar Basin
	medium and low pressure		The formation is oil-bearing, continuously distributed and fractured. The reservoir sweet area is enriched and highly productive.	Horizontal well volume fracturing to increase production.	Important resources of tight oil now	Chang 7' Chang 7' oil layer in Ordos basin
tight gas	water-bearing gas layer		The stratum is gas-bearing and continuously distributed, and the structural peak is enriched and high-yielding.	Water control and drainage to enhance recovery.	Important substitute resources for tight gas	Xujiahe Formation in central Sichuan Basin
	water-free gas layer		The coal measures are gas-bearing and continuously distributed. Favorable facies zone is enrichment and high yield.	Sand body characterization and horizontal well volume modification.	Important resources of tight gas now	Middle East Sulige, Ordos Basin
coal-bed methane	middle and low coal rank		The formation contains gas and is continuously distributed. The filling area with sufficient gas source is enriched and high-yielding.	Vertical well and other multi-well fracturing production.	Current replacement resources of coal-bed methane	Cretaceous of Erlian Basin
	middle to high coal rank		The formation contains gas and is continuously distributed. Gas-filled and hyperporous zones are enriched and high-yielding.	Vertical or cluster wells. Moderate transformation of horizontal well drainage gas development.	Important resources of coal-bed methane now	Carboniferous - Permian in Qinshui Basin
shale gas	onshore		The rich area of organic-rich laminated shale in deep water lacustrine basin is high-yielding.		Possible alternative resources of shale gas	Da 'anzhai Segment, North-central Sichuan Basin
	transitional facies		The organic-rich laminated shale in the transitional deep water area is gas-bearing and continuously distributed.	Horizontal well hydraulic volume fracturing and platform "artificial gas reservoir" volume development.	Important replacement resources for shale gas	Shanxi Formation, Ordos Basin
	marine		The organic-rich shale in the deep water shelf area is gas-bearing and continuously distributed.		Main resources for shale gas production	Wufeng - Longmaxi Formation in Sichuan Basin

Fig. 2. Theoretical understanding, key technologies and strategic positioning of unconventional shale strata oil and gas in China (Yang et al., 2021).

to the understanding of the mechanism for this process and the developments needed in the technical equipment.

In summary, the development of oil and gas reservoirs in different types of source rock strata faces different difficulties. For tight oil, the main challenge is the effective development of medium-and low-pressure parts; for tight sandstone gas, it is the effective utilization of water-bearing parts; for shale oil, it is the scaled development of medium and low maturity parts; for shale gas, it is the development of continental and marine-continental transitional parts; and for coal-bed methane, it is the supplementary development of low-rank coal. The next scientific and technological research phases will need to be further targeted for effectively solving these issues and maximizing the potential of these difficult-to-use resources (Fig. 2).

4. Development direction of source rock strata oil and gas in China

The source rock strata in China exhibit a rich accumulation of hydrocarbons. Natural gas in source rock strata will become the main force of natural gas production. Meanwhile, source rock strata will become the foundation of stable oil production, which have great development potential in the future.

Tight oil

- To carry out a new round of national classification evaluation of tight oil resources, the main enrichment zone for development needs to be selected and the "sweet area" that can be drilled must be identified.
- Research and development of applicable drilling and completion technologies are required to effectively cope with the low-and high-viscosity characteristics of onshore tight oil and to improve the production and recovery efficiency of single wells and blocks.
- To focus on the construction of tight oil national-level development demonstration zones in the Ordos, Songliao, and Junggar basins, a model for geology-engineering

integration of different types of tight oils is necessitated to promote the exploration and development of tight oil across the country.

Shale oil

- The construction of a national-level demonstration area is necessitated for continental shale oil in the Qingshankou Formation in the Songliao Basin.
- To focus on the construction of the national demonstration zone of the Permian onshore shale oil in the Junggar Basin for medium-and low-maturity shale oil, there is a need to effectively cope with the characteristics of medium and low pressures, difficult seepage flow, and difficult reformation of the onshore tight oil layers, while exploring effective development paths for low-grade and difficult-to-use reserves.
- For organic-rich shale exhibit medium and low maturities, there is a need to focus on the construction of a national continental shale oil demonstration area in the seventh member of the Triassic Yanchang Formation in the Ordos Basin and the Cretaceous Nenjiang Formation in the Songliao Basin, while exploring the formation of core technologies and equipment for underground in situ conversion.

Tight sandstone gas

- To deepen the understanding of tight sandstone gas enrichment rules, optimization of resource evaluation methods, implementation of national selection evaluation, and large-scale application of new resources is necessitated.
- For the areas with water-bearing tight sandstone gas in Ordos, Sichuan, and other basins where reserves are difficult to use, the bottleneck theory and technological research must be strengthened, the organization and management models must be optimized, tight gas fiscal policies and tax subsidy reductions must be established, and the applicability of low-grade reserves must be maximized.

- To develop key technologies such as high-precision, three-dimensional seismic, and large cluster horizontal wells, and to artificially stimulated fractures throughout the gas reservoir, intelligent engineering, improvement in the prediction accuracy of gas-bearing sand bodies, and increase in the production and recovery of single wells and blocks are necessitated.

Shale gas

- To strengthen the theoretical and technical research on the occurrence mechanism of non-marine shale gas, the Qiongzhusi Formation in the Sichuan Basin and other unbroken marine shale gas strata must be explored along with thin-bed precision drilling and effective fracturing. Furthermore, methods to achieve breakthroughs in new areas of shale gas extraction are required as soon as possible.
- The research and development of key technologies and equipment, such as the Wufeng-Longmaxi Formation marine deep shale gas volume fracturing technology and rotary steering tools, must be accelerated to support increase in production capacity.
- To establish a three-dimensional well pattern, a reasonable amount of well spacing and a production system template for marine shale gas blocks is required along with improved reserve production and block recovery for overall scale-benefit development.

Coal-bed methane

- The production and transformation tests must be consistent, as they promote stable production and increase the production in the old blocks of low-yield and low-efficiency coal-bed methane.
- The development of new production areas in the coal-bed methane development demonstration test will be beneficial in low coal rank and complex structure areas.
- The production area must be expanded for growth in coal-bed methane production due to the comprehensive development of deep and coal-derived natural gas.
- The construction of the underground coal gasification test areas in the Ordos, Junggar, and Erlian basins is necessitated, along with the exploration of the formation theory and core technical equipment required for underground coal gasification.

Overall, hydrocarbon accumulation in the source rock strata in China has great development potential in the future. Drawing on the unconventional oil and gas development path of source rock strata in the United States and focusing on basic geological research and scale-benefit development of different shale rock strata, it is still necessary to continuously increase investment in theoretical models and technological research and development, enhance the strength of independent innovation, and promote the construction of talent teams and laboratories. Consequently, China's source rock strata oil and gas resources will be further consolidated, and reserves and production will achieve substantial growth. After studying and judging the future strategic development direction, it is suggested to focus on creating and developing three underground projects based on artificially stimulated fractures in the oil

and gas reservoirs of source rock strata in China, namely: volume fracturing of oil and gas underground horizontal wells in source rock strata, in situ heating conversion processing of continental organic-rich underground shale, and in situ combustion gasification of the artificially stimulated fractures.

5. Conclusions

The focus of the source rock analysis is elucidating the sweet area selection and six-property relationship. These properties include the source rock, reservoir, oil-bearing, liquidity, fracture stimulation, and economy.

Targeted solutions to facilitate large-scale production and development of medium-and low-pressure tight oil, gas from water-bearing tight sandstones, low-rank coal-bed methane, continental and transitional shale gas, and medium-low mature shale oil are expected to be the key research directions for petroleum geology in China's onshore source rock strata over the next 15 years. If the sub-surface projects associated with two major ongoing underground projects based on artificially stimulated fractures in the oil and gas reservoirs, which involve in situ conversion processing of organic-rich shale into oil and gas and underground coal gasification, are successful, the strategic position of oil and gas source rocks will become even more important.

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Conflict of interest

The authors declare no competing interest.

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