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Editorial: Reservoir formation conditions and enrichment mechanisms of shale oil and gas

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Editorial on the Research Topic
Reservoir formation conditions and enrichment mechanisms of shale oil and gas

1 Introduction

In recent years, with the maturity of unconventional petroleum geological theory and the advancement of drilling and fracturing technologies, shale oil and shale gas have begun to gain commercial interest in some petroliferous basins of the terrestrial, marine and sea-land transition strata. Development, especially in Permian Basin, Illinois Basin, Appalachain Basin, Fort Worth Basin in North America, and China's Sichuan Basin, Junggar Basin, Bohai Bay Basin, Songliao Basin, and Ordos Basin have shown promising prospects for exploration.

Due to the variations in sedimentary and petrographic facies as well as tectonic evolution, the formation conditions and enrichment mechanisms of shales with various facies (terrestrial, marine, and sea-land transition facies) are also different. With the increased exploration activities, more drilling and logging data become available. In addition, advanced analysis and testing tools for cores are widely used. These allow for more in-depth studies on the formation mechanisms, shale sequences, shale sedimentation, shale reservoirs, shale oil and gas formation and enrichment of the organic-rich shales with different facies, which will facilitate the discovery of new geological theories and understanding.

This Research Topic, focusing on the geological theory related to shale oil and gas in terrestrial, marine, and sea-land transition facies, aims to present the latest research progress on each topic and the application of shale oil and petroleum geological theory in major hydrocarbon-bearing basins.

2 Research on shale deposition

The Chang 7 black shale in the Upper Triassic Yanchang Formation is the principal source rock of Mesozoic oil-bearing system in the southwest Ordos Basin, containing high abundances of organic matter and hydrocarbon potential. Yuan et al. study discusses the role of lake-bottom hydrothermal activities in the enrichment of organic matter during the deposition of the Chang 7 black shale.

Shanxi Formation Shan 2^3 Submember transitional shale in Eastern Ordos Basin is characterized by high TOC value, wide distribution, and large single-layer/cumulative thickness. In Gu et al. study, based on section division of Shan 2^3 Submember, petrographic, mineralogical, and high-resolution geochemical analyses were integrated to reveal sedimentary environment, detrital influx, paleoclimate, paleosalinity, and paleoredox conditions.

In Li et al. study, rock pyrolysis, organic petrology, vitrinite reflectance, gas chromatography-mass spectrometry (GC-MS) analysis, and biomarker compound analysis were performed to comprehensively analyze the organic geochemical characteristics of the Jurassic Da'anzhai Member (J_1da) shale strata in Yuanba and Puguang areas in the northeastern Sichuan Basin. Then the organic matter provenance and sedimentary environment were further analyzed. Finally, the significance of oil and gas exploration in J_1da shale strata was discussed.

For a more in-depth analysis on the marine chemical condition during the earliest Cambrian, mechanism of organic matter enrichment and exploration potential of shale gas resources, based on the petrology, organic geochemistry, and elemental characteristics of the W207 Well, Zhao et al. study discuss the Early Cambrian paleo-ocean environment and factors controlling of organic matter enrichment during the deposition of black strata Qiongzhusi Formation in the upslope areas, southwestern Sichuan Basin, Yangtze Block, China.

The lithofacies assemblages in the lacustrine shale of the Shahejie Formation in the Dongying Depression have different compositions due to the complex depositional climate, lake water conditions, and sediment supply. In Li et al. study, the lithofacies types and depositional conditions were analyzed based on parasequence division and lithofacies classification.

In Cao et al. study, reservoir space development characteristics and the geochemical parameters of the Permian Longtan Formation in the southeast of the Sichuan Basin at Well X1 was analyzed by using core observations, optical thin-section observations, Ar-ion polishing, scanning electron microscopy, and nitrogen adsorption tests. Major and trace elements of samples, the V/Cr, U/T, enrichment coefficients EF (Mo) and EF (U), chemical alteration indexes CIA and Sr/Cu, and Mo, P, and other index values of different samples were calculated based on the test of organic geochemical parameters. The depositional environment of the Longtan Formation in the study area was systematically analyzed.

In Gu et al. study, The Upper Permian Linghao Formation marine shale and contemporaneous transitional shale are the most potential shale gas targets in the Nanpanjiang basin, which is characterized by considerable TOC content, wide distribution, and considerable shale thickness. On the basis of division in Linghao Formation, petrographic, mineralogical, and high-resolution geochemical analyses were integrated to reveal the sedimentary environment including paleoproductivity, paleoredox conditions, detrital influx, paleoclimate, and the paleosalinity.

In Tang et al. study, due to the dual effects of fluvial and tides, the tidal sand bars in estuaries have complex sedimentary characteristics and complex internal structures, making them difficult to predict and describe. In this paper, the sedimentary dynamics numerical simulation method is used to establish a tidal-controlled estuary model. The effects of tidal range and sediment grain size on tidal sand bars are simulated. The length, width, and thickness of tidal sand bars, as well as the length and thickness of the internal shale layer, are also analyzed.

In Dong et al. study, the distribution characteristics and formation of marine anoxic conditions through the Late Ordovician–Early Silurian (O–S) remain poorly resolved despite their importance in the preservation of sedimentary organic matter and the formation of black shale. In this study, the major, trace, and pyrite δ34S (δ34Spy) contents of 36 shale samples at the edge of the southwest depocenter of the Upper Yangtze Basin (Tianlin and Changhebian sections) were analyzed to understand the redox conditions, terrigenous clastic inputs, and primary productivity changes.

In Yang et al. study, this research studied the genetic types, dynamic mechanisms, and sedimentary models of the gravity-flow deposits of the Chang 6 oil group in the Heshui Area, Ordos Basin, China, aiming to reveal its petroleum geological significance. Core observation, microscopic thin section identification, particle size analysis, and determination of rare earth elements were carried out.

In Wang et al. study, the paleoenvironment during the Early Cambrian is closely related to the accumulation mechanism of organic matter (OM) from the Lower Cambrian black shales. However, paleoenvironment remains a controversial issue. Here, we reported a lot of detailed data of sedimentary stratigraphy and geochemistry of the Lower Cambrian Yuertusi Formation in the Aksu area, Tarim Basin.

In Shen et al. study, mechanism of the organic matter (OM) accumulation in the Middle Permian Gufeng Formation shale in South China is lack of constraints, which restricts the source rock evaluations and shale gas explorations. To decipher the OM accumulation of the Gufeng Formation, geological and geochemical results related to paleo-environmental variations are presented from the shelf Putaoling section in South China.

3 Influence of tectonic evolution on shale gas accumulation

Li et al. study has investigated the Longmaxi shale from two well locations in Chongqing and Hunan in order to understand whether differences in pore structure are the cause of the difference in commerciality in the two areas. The formation burial histories were established, analyzing samples for mineral composition, total organic carbon (TOC) content, thermal maturity (Ro), and OM pore structures.

In He et al. study, preservation conditions are the key factors that determine the effective accumulation of shale gas. The damage of faults formed by differential structures to the roof and floor and the shielding of lateral edges are the direct reasons for the difference in preservation conditions. Taking the organic-rich shale of the Wufeng–Longmaxi Formation in the south of the Sichuan Basin as an example, this paper reveals different types of shale gas-rich structures by using typical seismic profiles and puts forward the main controlling factors of different gas-rich structures and their influence on preservation.

In Wang et al. study, the Longmaxi Formation in the southern Sichuan Basin is an important target for shale gas exploration and development. The characteristics and stages of structural development significantly impact shale gas preservation and enrichment. Taking the Longmaxi Formation in the Yanjin–Junlian area of the southern Sichuan Basin as an example and based on the results of surface and underground structural analysis, fluid inclusion tests, apatite fission track experiments, and burial-thermal evolution history analysis, a comprehensive study of the development characteristics and structural stages of the Longmaxi Formation was carried out, and an evolution model was developed.

4 Research on the characteristics of shale reservoirs

In Yuan and Yang study, mud shale can serve as source or cap rock but also as a reservoir rock, and so the development of pores or cracks in shale has become of great interest in recent years. However, prior work using non-identical samples, varying fields of view and non-continuous heating processes has produced varying data. The unique hydrocarbon generation and expulsion characteristics of shale as a source rock and the relationship with the evolution of pores or cracks in the reservoir are thus not well understood.

In Zhang et al. study, marine–continental transitional (hereinafter referred to as transitional) Permian shales are important targets for shale gas in China because of the considerable volumes of shale gas resources present in them. In this study, transitional shale samples from the Permian Shanxi Formation in the Daning–Jixian block along the eastern margin of the Ordos Basin were collected to investigate the effects of organic and inorganic compositions on the development of their pore structures through organic petrographic analysis, X–ray diffraction, scanning electron microscope (SEM) observation, gas (N_2 and CO_2) adsorption, high-pressure Mercury injection (HPMI), and methane adsorption experiments.

In Guo et al. study, organic-rich shale and associated fine-grained sedimentary rocks of marine-continental transitional facies were well developed in the Upper Carboniferous Keluke Formation in the Eastern Qaidam Basin, which is expected to be a set of potential shale gas exploration and development target. Mineralogy and pore structure of marine-continental transitional shale were investigated systematically based on thin-section identification, X-ray diffraction (XRD), helium porosity test and pressure-pulse permeability measurement, scanning electron microscopy (QEMSCAN), field emission scanning electron microscopy (FESEM), and high-pressure Mercury injection (MICP) and nitrogen adsorption.

With the development of unconventional oil and gas exploration "from sea to land," lacustrine fine-grained sedimentary rocks (FSR) have gradually attracted the attention of scholars and become an important topic in the field of unconventional oil and gas, but the research is still in its initial stage. In Yang et al. study, lacustrine FSR in the Dongying Depression of the Bohai Bay Basin are used as the research object, and nuclear magnetic resonance (NMR) and quantitative image characterization are used to characterize the pore structure of the reservoir in the study area on multiple scales, analyze the reservoir characteristics control factors, and classify and evaluate the reservoir.

In Du et al. study, Investigation of pore structure is vital for shale reservoir evaluation and also "sweet spot" prediction. As the strong heterogeneity in pore types, morphology, and size distributions of organic matter-rich shales, it is essential to combine different approaches to comprehensively characterize them. Field emission-scanning electron microscopy (FE-SEM), low-pressure gas (CO_2 and N_2) adsorption, and high-pressure Mercury intrusion (HPMI) were employed to systematically investigate the pore structure of the lower Longmaxi shale reservoirs in the northern Guizhou area.

In Zhao et al. study, in most organic-rich shale reservoirs, dolomite is widely distributed and has different types and crystal sizes. However, the characteristics and formation mechanism of the dolomites in organic-rich shale are still poorly understood. Petrographic and geochemical analyses were performed to interpret the formation of dolomite in the lacustrine organic-rich shale of the Shahejie Formation, Dongying Sag, Bohai Bay Basin.

In Jiang et al. study, the major sedimentary basins in China contain abundant shale gas resources to be explored, and the exploration of shale gas has received more attention in recent years. Shale gas exists mainly in two states, i.e., free and adsorbed. The latter mainly exists on the surface of media, including organic matter and clay minerals, etc., but its adsorption state

remains unknown. In this paper, we take the Longmaxi Formation marine shale in the southern Sichuan Basin of southern China as the research object. The state of methane molecule adsorption on different media in marine shales is analyzed by conducting mineral composition analysis, TOC content analysis, isothermal adsorption experiments, FIB-SEM, and FIB-HIM experiments on the core samples referring to previous research.

In Liang et al. study, in present paper, the mineral and fluid compositions of shale oil from the Songliao Basin are analyzed systematically using core samples, X-ray diffractometer (XRD), and gas chromatography (GC). The effects of shale mineral composition, pore size, temperature, and pressure on the mass density of the adsorbed layers are then studied utilizing molecular dynamics simulation.

In Wang et al. study, the Lower Permian Shanxi Formation in the Eastern Ordos Basin is a set of transitional facies shale, and it is also a key target for shale gas exploration in China. Based on lithofacies classification by X-ray diffraction and kerogen type identification, nanoscale reservoir space, pore volume, pore size distribution, surface area, and fractal characterization were studied using comprehensive methods including N_2 and CO_2 adsorption, Mercury injection capillary pressure, field emission-scanning electron microscopy (FE-SEM), and nuclear magnetic resonance.

In Chen et al. study, pyrite is widely distributed in the Longmaxi marine shale in the Upper Yangtze area of China. Pyrite, one of the important components of shale, has an important influence on the enrichment of shale gas. However, there are currently only a few studies on this topic. Based on shale samples from drilling cores using field emission scanning electron microscopy, the pore characteristics of pyrite from the Longmaxi Formation in the Upper Yangtze area of China are studied.

In Miao et al. study, both Lower Cambrian and Lower Silurian shale are typical of oil-prone kerogen and siliceous composition, but differ in thermal maturities with 3.56% Ro and 2.31% Ro, respectively. In this paper, pore characteristics were explored between these two shales. All samples were studied by a combination of organic geochemistry, x-ray diffraction, N_2 adsorption, helium porosity, and focused ion beam milling and scanning electron microscopy. In particular, N_2 adsorption of isolated OM was conducted to compare physical properties of OM-hosted pores, and fractal dimension was exploited to analyze morphologic characteristics of pores.

5 Evaluation and target optimization of shale oil and gas reservoirs

In He et al. study, to investigate the geological characteristics and exploration potential of shale gas in the southern Sichuan Basin, we analyze the coupling relationship between the hydrocarbon generation and storage conditions of the Longmaxi Formation and discuss the preservation conditions from the lateral and vertical migration mechanisms of shale gas.

In Wang et al. study, large amounts of conventional gas resources that originated from terrestrial Lower Jurassic shale were discovered in the Tarim Basin, indicating promising exploration prospects for shale gas resources, whereas limited understandings were obtained on the geological and geochemical characteristics of the Lower Jurassic shale. In this study, based on cores of exploration wells and field outcrops, total organic carbon (TOC) pyrolysis, microscopic composition, organic elements, vitrinite reflectance, x-ray diffraction, and methane isothermal adsorption experiments were carried out on Lower Jurassic shale in the Tarim Basin.

In He et al. study, fine-grained sedimentary rock (FGSR) reservoirs in a deep-water sedimentary environment from the Late Triassic Yanchang Formation in the Ordos Basin in central China have huge potential for tight oil production. According to the comprehensive research of fluid inclusion experiment, scanning electron microscopy, cathodoluminescence, thin section identification, and whole rock analysis, the petrographic characteristics, fluorescence spectrum parameters, and the homogenization temperature of oil inclusions and associated brine inclusions in the FGSR reservoir were analyzed to explore the coupling relationship between densification characteristics and tight oil accumulation of the FGSR reservoir.

In Zeng et al. study, the organic-rich shale of the early Carboniferous Jiusi Formation in the Weining area, Southwestern China, has large geological gas reserves, making the Jiusi Formation another target after the Ordovician-Silurian marine shale in South China. The complex superposition of multi-stage tectonic phases since the Himalayan paroxysmal phase has induced a series of controversies in the sedimentology of the Jiui Formation, as only a few drillings were executed. In order to better understand the development potential of the shale associated with the Jiui Formation, five outcrops and a well (YS302) were studied, clarifying the sedimentary evolution of the formation, while two 2D seismic sections were used to analyze the regional structural styles.

In Tang et al. study, lower Permian Fengcheng Formation is considered to be a high-quality alkaline lacustrine shale oil resource in the Junggar Basin, NW China. Based on core and thin section observation, X-ray diffraction, scanning electron microscope, low-pressure N2 adsorption, and high-pressure Mercury intrusion porosimetry, different shale lithofacies, and pore structures were examined.

In Hu et al. study, the classification method of karst formations is widely used in engineering and environmental geology but is seldom used in petroleum geology. In this study, the classification method of karst formations is applied to the sealing study of shale gas roof and floor carbonate rocks, and the influence on shale gas accumulation and drilling is discussed. The

Paleozoic black shale in southern China is primarily formed by marine and transitional faces, and the intergrowth between shale and carbonate rocks is a basic geological feature of the Paleozoic strata in southern China. Carbonate karst is an unavoidable problem in shale gas exploration in southern China. Around the black shale target layer, in the Upper Paleozoic trait region, the study starts from the development strength of karst strata, through geological profile survey, spring flow statistics, test, and other methods and means; the shale and the carbonate rock contacted with it are taken as a whole to explore the impact of karst strata on shale gas drilling.

In Chen et al. study, to clarify the implication of alkane carbon and hydrogen isotopes for the genesis and accumulation of over-mature shale gas, we carried out a comparative study on Longmaxi shale gases from eight blocks in the Upper Yangtze area. The results show that the $\delta^{13}CCH_4$, $\delta^{13}CC_2H_6$, and $\delta^{13}CC_3H_8$ of Longmaxi shale gas are all positively correlated with Ro. According to the distribution model of $\delta^{13}C$ with thermal maturity, the Longmaxi shale gas lies in the reversal stage. Shale gas is a mixture of the kerogen cracking gas and secondary cracking gas, and the mixing ratio of the two cracking gas can be estimated by isotopic fractionation experiments of thermogenic gas.

In Cheng study, by means of thin section authentication, physical characteristics analysis, scanning electron microscopy (SEM), X-ray diffraction, and vitrinite reflectance analysis, this paper, based on regional geological research achievements, studies the sedimentary facies and diagenesis of the southern and northern Silurian Xiaoheba Formation areas of Southeast Sichuan and their relationships with the physical characteristics of the reservoirs.

In Dong et al. study, The Jurassic Shaximiao Formation in western Sichuan has made significant contributions to the natural gas reserves and production of China, with many gas fields successively discovered. The accumulation evolution progress and discrepant gathering law are continuously improved with the constantly deepened exploration and development. In order to find evidence for the difference in gas accumulation and the method to reshape the migration and accumulation of natural gas and their dynamic processes based on time and space, this study analyzes the dynamic accumulation process of the Middle Jurassic Shaximiao reservoir in the Zhongjiang gas field using the geochemical parameters, including the conventional composition of natural gas, light hydrocarbon components, carbon isotope, and formation water, of more than 160 natural gas samples from 155 wells.

In Wei et al. study, various studies have shown that geo-catalytically mediated methanogenesis could happen in immature to early-mature source rocks at temperatures ranging from 60 to 140°C based on a series of long-term laboratory heating experimental evidences. The results of those studies show that methane yields at the given temperature are 5–11 orders of magnitude higher than the theoretically predicted yields from early thermogenic methane generation kinetic models. However, different types of source rocks in these laboratory simulation experiments generated varied CH_4 and CO_2 yields, which suggest that controls on CH_4 generation during catalytic methanogenesis are complex. This study summarizes and compares gas yield results from laboratory low-temperature heating simulation experiments. Pre-existing trapped methane in rock chips could mimic newly generated gas during heating. The yields of catalytically generated CH_4 from individual source rocks were re-quantified by subtracting the amounts of pre-existing CH_4 in the closed pores of the original source rocks from the total methane amounts released from heating experiments and pre-existing CH_4 in the closed pores in heated source rocks. The results show that heating temperature and time exert a positive influence on methane catalytic methanogenesis.

In Gu et al. study, the Upper Permian Linghao Formation shale is the most potential shale gas exploration target in Nanpanjiang Basin. In this study, X-ray diffraction, field emission scanning electron microscopy, CH_4 isothermal adsorption, and nuclear magnetic resonance cryoporometry are intergrated to reveal comprehensive characterization of Linghao Formation shale collected from a well in Nanpanjiang Basin.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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