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Geological conditions and reservoir characteristics of various shales in major shale-hosted regions of China

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ABSTRACT

China is home to shales of three facies: Marine shale, continental shale, and marine-continental transitional shale. Different types of shale gas are associated with significantly different formation conditions and major controlling factors. This study compared the geological characteristics of various shales and analyzed the influences of different parameters on the formation and accumulation of shale gas. In general, shales in China's several regions exhibit high total organic carbon (TOC) contents, which lays a sound material basis for shale gas generation. Marine strata generally show high degrees of thermal evolution. In contrast, continental shales manifest low degrees of thermal evolution, necessitating focusing on areas with relatively high degrees of thermal evolution in the process of shale gas surveys for these shales. The shales of the Wufeng and Silurian formations constitute the most favorable shale gas reservoirs since they exhibit the highest porosity among the three types of shales. These shales are followed by those in the Niutitang and Longtan formations. In contrast, the shales of the Doushantuo, Yanchang, and Qingshankou formations manifest low porosities. Furthermore, the shales of the Wufeng and Longmaxi formations exhibit high brittle mineral contents. Despite a low siliceous mineral content, the shales of the Doushantuo Formation feature a high carbonate mineral content, which can increase the shales' brittleness to some extent. For marine-continental transitional shales, where thin interbeds of tight sandstone with unequal thicknesses are generally found, it is recommended that fracturing combined with drainage of multiple sets of lithologic strata should be employed to enhance their shale gas production.

1. Introduction

Shale gas, a type of natural gas, is generated from organic-rich shales and occurs in free, adsorbed, or dissolved states (Li JQ and Cai JC, 2023). It is a type of unconventional natural gas characterized by hydrocarbon generation and accumulation in the same shale reservoirs, as well as an extensive and continuous distribution (Curtis JB, 2002). Artificial stimulation, such as staged fracturing of horizontal wells, is required to obtain commercial gas flow from shale formations (Cui QC et al., 2023), which, thereby, are also known as artificial gas reservoirs.

The organic-rich shales in China were formed in marine, marine-continental transitional, and continental sedimentary environments from the Precambrian to the Neogene. The marine organic-rich shales are distributed primarily in the pre-Paleozoic and Paleozoic formations in South China, North China, and the Tarim Basin. Such formations in South China include the Upper Sinian Doushantuo Formation, the Lower Cambrian Niutitang Formation, the Upper Ordovician Wufeng Formation, the Lower Silurian Longmaxi Formation, the Middle-Upper Devonian Yintang and Luofu formations, and the Lower Carboniferous Jiusi Formation. Formations containing marine organic-rich shales in North China consist of the Upper Proterozoic Chuanlinggou, Hongshuizhuang, and Xiamaling formations and the Middle Ordovician Pingliang Formation. Such formations in the Tarim Basin primarily comprise the Lower Cambrian Yuertusi Formation

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and the Middle-Upper Ordovician Saergan and Yingan formations. Marine-continental transitional organic-rich shales in China are distributed in the Permian Liangshan and Longtan formations in South China, as well as the Carboniferous Permian Benxi, Taiyuan, and Shanxi formations in North China. The continental organic-rich shales can be found in the Upper Triassic Xujiahe Formation and the Middle-Lower Jurassic Ziliujing Formation in the Sichuan Basin, as well as the Permian Jiamuhe and Fengcheng formations and the Lower Wuerhe Formation in western China. Furthermore, formations contain continental organic-rich the shales of the Ordos Basin include the Upper Triassic Huangshanjie Formation, the Jurassic Badaowan, Sangonghe, Xishanyao, Yangxia, and Kezilenuer formations, and the Upper Triassic Yanchang Formation. Additionally, shales are also found in formations in the Songliao Basin and the Bohai Bay Basin, with the former including the Cretaceous Qingshankou and Shahezi formations and the latter dominated by the Paleogene Shahejie and Kongdian formations (Table 1; Fig. 1; Dong DZ et al., 2016; Zhang JC et al., 2016).

Although commencing late in 2009, the shale gas exploration and exploitation of China have developed rapidly. So far, shale gas fields such as Fuling, Changning, and Weiyuan have been discovered in the Sichuan Basin (Zhao WZ et al., 2020). By November 2022, China had achieved 2.75×10^{12} m^3 of cumulative proven geological reserves of shale gas, including a shale gas output of 22.9×10^{9} m^3 in 2021, which accounts for over 10% of China's natural gas output that year. For shale gas fields in South China, the primary targets include the marine shales of the Ordovician Wufeng Formation and the Silurian Longmaxi Formation. High test outputs of shale gas have been obtained through drilling from marine shales of the Sinian Doushantuo Formation and the Cambrian Niutitang Formation in the northern portion of the central Yangtze area. Significant shale gas shows have been observed in the marine-continental transitional shales of the Permian Longtan Formation in western Guizhou (Wang SJ et al., 2020). Additionally, high test outputs of shale gas have been obtained through drilling from continental shales of the Triassic Yanchang Formation in the Ordos Basin and the Cretaceous Qingshankou Formation in the Songliao Basin.

Three types of shale gas were formed and accumulate under different sedimentary facies (Zou CN et al, 2011). Currently, all shale gas fields discovered in China originate from marine sedimentary shales. In addition, shale gas discoveries have also been made in continental and marine-continental transitional shales in many regions. Therefore, the three types of shales possess favorable geological conditions for shale gas formation and accumulation (Ma YS et al., 2018). Under different tectonic settings and sedimentary environments, shales of different types in different regions and periods differ significantly in organic geochemistry, reservoir quality, rock mineralogy, and gas-bearing capacity. Furthermore, the principal geological characteristics of the

Table 1. Organic-rich shale of mainly onshore oil gas-bearing basins in China (modified from Dong DZ et al., 2016).

Period	System	Series	Tarim Basin	Junggar Basin	Qaidam Basin	Sichuan Basin	Other regions in the south	Songliao Basin	Bohaiwan Basin	Ordos Basin
Cenozoic	Paleogene	Oligocene							Dongying	
		Eocene							Shahejie	
		Paleocene							Kongdian	
Mesozoic	Cretaceous	Upper						Qingshankou		
		Lower						Shahezi		
	Jurassic	Middle	Qiakemake	Xishanyao	Dameigou	Shaximiao				
		Lower	Yangxia	Sangonghe	Huxishan	Ziliujing				
	Triassic	Upper	Taliqike	Baijiantan		Xujiahe				Yanchang
Upper Paleozoic	Permian	Upper				Longtan	Longtan			
		Middle		Lower Wuerhe					Shanxi	
		Lower		Fengcheng					Taiyuan	
	Carboniferous	Upper		Bashan	Keluke				Benxi	
		Lower					Jiusi			
	Devonian	Middle					Luofu			
Lower Paleozoic	Silurian	Lower				Longmaxi	Longmaxi			
	Ordovician	Upper	Yingan			Wufeng	Wufeng			
		Middle	Sargan							Pingliang
		Lower	Heituao							
	Cambrian	Lower	Yuertus			Niutitang	Niutitang			
Proterozoic	Sinian	Neoproterozoic				Doushantuo	Doushantuo			
	Daijian	Mesoproterozoic							Xiamaling	
	Jixian								Hongshuizhuang	

Note: Blue represents marine shale; Yellow represents marine-continental transitional shale; Green represents continental shale.

Fig. 1. Geographical location map of the study area.

three types of shales, as well as the formation conditions of shale gas, are also significantly distinct (Dong DZ et al., 2016).

Overall, marine shales in China exhibit highly abundant organic matter, a high brittle mineral content, and a high degree of thermal evolution. By contrast, marine-continental transitional shales demonstrate highly abundant organic matter but a low brittle mineral content and a low degree of thermal evolution, which account for the failure in the effective production of these shales. The comprehensive comparison of various shales' geological characteristics based on the abovementioned characteristics is a major challenge for the targeted survey and exploration of various shale gas.

2. Sedimentary facies types of shales

2.1. Shales of the Sinian Doushantuo Formation and the Cambrian Niutitang Formation in western Hubei

Western Hubei is situated in the northern portion of the Central Yangtze Plate in South China. During the deposition of the Doushantuo Formation, a significant marine transgression occurred in two sedimentary units in western Hubei: the central and western Hubei platforms. The main body of the platforms originated from a relatively deep-water sedimentary environment, which provided favorable conditions for the generation and preservation of organic matter. Western Hubei serves as a dominant region for the occurrence of organic-rich black shales of the Doushantuo Formation, which primarily comprise gray, grayish-black, and black argillaceous dolomites and shales. Based on the lithological characteristics, the Doushantuo Formation can roughly be divided into four members, with organic-rich black shales primarily found in the second member (Zhang JF et al., 2019).

During the Early Cambrian, a large-scale marine transgression occurred in the entire Yangtze region, causing water bodies to deepen gradually from northeast to southwest in western Hubei. The shales of the Lower Cambrian Niutitang Formation were deposited progressively from shallow- to deep-water shelves, consisting predominantly of grayish-black and black shales mixed with marlstones. Based on the lithological characteristics, the Niutitang Formation can be roughly divided into three members, with organic-rich black shales also primarily distributed in the second member (Zhang JF et al., 2019).

2.2. Shales of the Ordovician Wufeng Formation and the Silurian Longmaxi Formation in the Sichuan Basin

Currently, the organic-rich shales of the Wufeng and Longmaxi formations in the Sichuan Basin play a vital role in

China's shale gas exploration and production (Zou CN et al., 2015; Dong DZ et al., 2014, 2016; Zhao WZ et al., 2016). From the Late Ordovician to the Early Silurian, the Yangtze and Cathaysian plates converged continuously under the influence of the Caledonian movement and the relentless action of the compressive stress in eastern South China, leading to the continued uplift of the Jiangnan-Xuefeng, central Guizhou, and central Sichuan regions (Wang Z et al., 2013; Cai QS et al., 2020). Consequently, the sedimentary environment of the Yangtze Plate shifted from the platform facies to the shelf facies. Besides, the Sichuan Basin grew into a restricted detention basin surrounded by several ancient continents, with a set of thick shales of the Wufeng and Longmaxi formations deposited in the basin (Chen X et al., 2004; Yan DT et al., 2008; Liu W et al., 2012; Zhang JY et al., 2017).

2.3. Shales of the Permian Longtan Formation in western Guizhou

Western Guizhou is located in the west-central part of the Yangtze Plate in South China. Since the Middle Permian, many marine-continental transitional coal-bearing strata in the Longtan Formation have been deposited in the study area, with the sedimentary environment principally comprising the lagoon, tidal-flat, deltaic, and swamp facies (Shao LY et al., 2013). Deposited in this transitional environment, the Longtan Formation is generally thick and exhibits intricate lithologies consisting primarily of carbonaceous shales, carbonaceous mudstones, silty mudstones, argillaceous siltstones, siltstones, and multiple sets of thin coal seams. Shales in this formation are characterized by many layers, with a small single-layer thick and a considerable cumulative thickness (Deng ED et al., 2020).

2.4. Shales of the Triassic Yanchang Formation in the Ordos Basin

The Ordos Basin is situated in Central China. In the early depositional stage of the Yanchang Formation during the Late Triassic, significant tectonic activity caused the rapid expansion of the lake basin, forming extensive deep-water sediments, which led to the boom in aquatic organisms and plankton, rich organic matter, and massive lacustrine shales (Er C et al., 2015). As continental rock series of the lacustrine-fluvial facies primarily, the shales of the Yanchang Formation serve as the primary source rock series in the basin (Li WH et al., 2009). The 7th member of the Yanchang Formation, one of the most significant source rocks, are deposits dominated by dark-gray and grayish-black mudstones, shales, and oil shales, mixed with a small amount of thinly laminated siltstones (Jiang CF et al., 2013; Zhang YY et al., 2013).

2.5. Shales of the Cretaceous Qingshankou Formation in the Songliao Basin

The Songliao Basin, situated in Northeast China, is a large-scale continental petroliferous basin. The depositional period of the Qingshankou Formation witnessed the rapid subsidence and evolution of the transgressive systems tract in the Songliao Basin (Yang LY et al., 2005; Ge MN et al., 2019). During this period, the Songliao Basin underwent expansion as a lake basin, with dark mud and shales deposited in the 1st member of the Qingshankou Formation. The sedimentary facies in the basin include the outer delta front facies and the semi-deep and deep lacustrine facies. The 1st member of the Qingshankou Formation primarily comprises grayish-black and dark-gray shales, mixed with oil shales, gray sandstones, and siltstones (Niu JH et al., 2010; Liu C et al., 2017).

3. Geological characteristics of various shales

3.1. Thicknesses of organic-rich shales

The organic-rich shales of the Doushantuo and Niutitang formations in western Hubei have thickness ranges of 50–110 m and 9–140 m, respectively (Zhang JF et al., 2019; Zhai GY et al., 2020). The shales of the Wufeng and Longmaxi formations in different regions of the Sichuan Basin display varying thicknesses. Specifically, they are 20–90-m-thick in the Fuling area, 20–60-m-thick in the Changning and Zhaotong areas, and 30–50-m-thick in the Weiyuan area (Zou CN et al., 2011; Dong DZ et al., 2014; Wang YM et al., 2014). The shales of the coal-bearing layers of the Permian Longtan Formation in western Guizhou show different thicknesses. In well Jinshacan 1, the marine-continental transitional coal-bearing strata in the Longtan Formation have a total thickness of approximately 120 m, including a cumulative shale thickness of around 45 m. This formation exhibits frequently alternating shales, sandstones, and coal seams, suggesting pronounced vertical heterogeneity (Deng ED et al., 2020). The shales of the 7th member of the Yanchang Formation in the Ordos Basin have thicknesses generally from 70–80 m and up to over 100 m (Wang XZ et al., 2015). The 1st member of the Qingshankou Formation in the Songliao Basin is generally thick and unevenly distributed, with thicknesses primarily between 50–200 m (Dong DZ et al., 2016).

3.2. Geochemical characteristics of shales

Black shales of the Sinian Doushantuo Formation and the Cambrian Niutitang Formation were encountered during the drilling of the well Eyangye 1 in western Hubei, with organic matter dominated by type I. Black shales of the Doushantuo Formation have TOC contents of 0.18%–8.20% (average: 2.26%) and maturity of 3.00%–3.94% (average: 3.24%). Furthermore, they show a maximum field desorbed gas content of 2.21 m^3/t and a maximum total gas content of 4.82 m^3/t. Black shales of the Niutitang Formation have TOC contents of 0.30%–8.72% (average: 3.22%) and maturity of 2.55%–3.06% (average: 2.84%; Table 2; Fig. 2). These shales exhibit a maximum field desorbed gas content of 2.16 m^3/t and a maximum total gas content of 4.48 m^3/t.

The shales of the Wufeng and Longmaxi formations in the Sichuan Basin primarily contain type I organic matter,

Table 2. Evaluation parameters of the six sets of shale.

Area	Age	Name	Thickness/ m	Type	TOC/ %	*Ro*/ %	Porosity/ %	Quartz + feldspar/ %	Carbonate/ %	Clay/ %	References
Western Hubei	Sinian	Doushantuo	50–110	I	0.18–8.20/ 2.26	3.00–3.94/ 3.24	0.28–3.47/ 1.76	10.40–50.50/ 31.10	20–34.6/ 53.2	0.2–24/ 15.7	Zhai GY et al., 2020; Zhang JF et al., 2019
Western Hubei	Cambrian	Niutitang	9–140	I	0.30–8.72/ 3.22	2.55–3.06/ 2.84	0.09–6.26/ 3.03	19–76.6/ 54.1	10.7–71.9/ 25.9	3.9–25.8/ 14.9	Wang YM et al., 2014; Zhai GY et al., 2020
Sichuan Basin	Ordovician-Silurian	Wufeng-Longmaxi	20–90	I – II	0.40–9.60/ 2.55	2.30–3.80/ 2.80	2.8–7.1/ 4.65	40–85.9/ 62.78	2–22.9/ 7.5	10.8–54/ 29.7	Zou CN et al., 2011
Northern Guizhou	Permian	Longtan	2–45	III	1.30–9.58/ 4.20	2.42–2.82/ 2.51	2–4.2/3	2.20–60.95/ 37.88	20.15–97.8/ 56.48	0–53.45/ 6.83	Dong DZ et al., 2014
Ordos Basin	Triassic	Yanchang	70–80	II	1.60–7.20/ 4.60	0.80–1.30/ 1.20	0.16–5.12/ 2.11	12.60–55.90/ 40.50	0–27.4/ 1.76	31.4–86.7/ 57.7	Du Y et al., 2020
Songliao Basin	Cretaceous	Qingshankou	50–200	I – II	0.32–3.52/ 2.04	0.81–1.13/ 0.91	0.65–5.55/ 1.72	37–68/ 49.2	0–26/ 7.73	27–55/ 43.1	

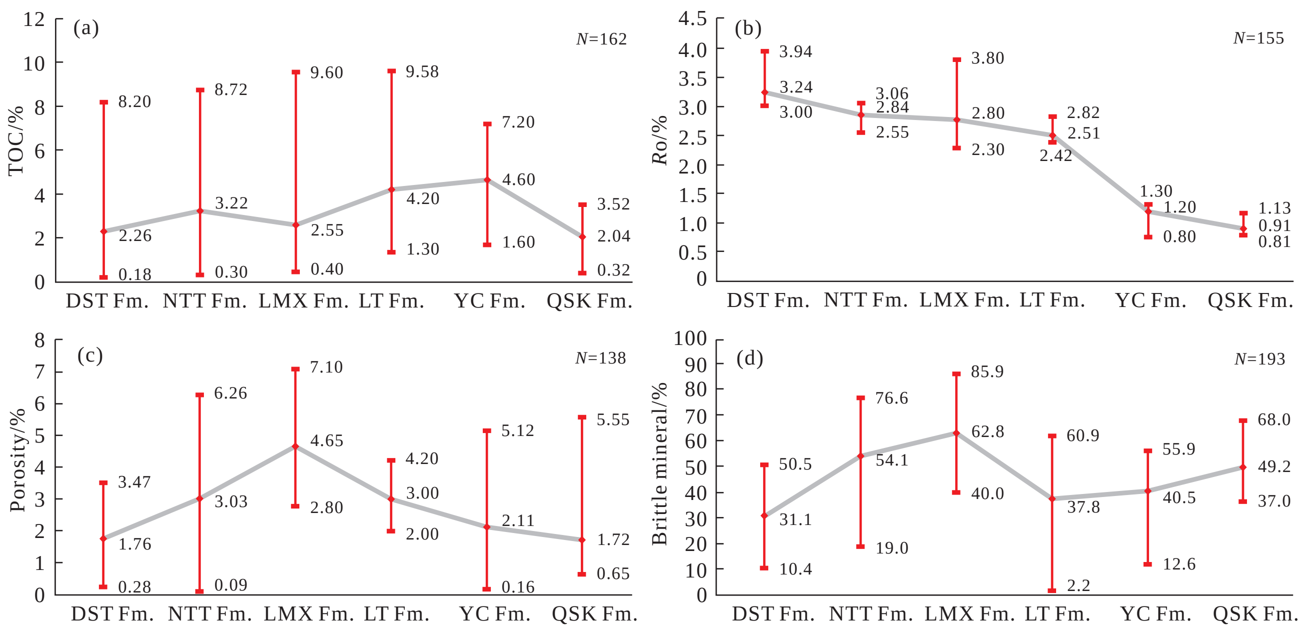

Fig. 2. TOC (a), *R*o (b), porosity (c), and Brittle mineral (d) features of different types of shales. DST Fm.–Doushantuo Formation; NTT Fm.–Niutitang Formation; LMX Fm.–Longmaxi Formation; LT Fm.–Longtan Formation; YC Fm.–Yanchang Formation; QSK Fm.–Qingshankou Formation.

followed by a small amount of type II organic matter. Their TOC contents vary in the range of 0.4%–9.6% (average: 2.55%), generally exceeding 2% at the bottom of the Longmaxi Formation. They have maturity of 2.3%–3.8%, averaging approximately 2.8% (Table 2; Fig. 2), and total gas contents of 1.28–6.47 m^3/t, with an average of 3.27 m^3/t (Zou CN et al., 2010, 2020; Li J et al., 2021).

The shales of the Longtan Formation in western Guizhou primarily contain type III organic matter. They have TOC contents of 1.30%–9.58% (average: 4.20%), exceeding 2.0% in the main body. The disorderly vertical distribution of the TOC contents is chiefly caused by the strong heterogeneity of coal-bearing strata in the Longtan Formation and frequently alternating lithologies. They have a maturity of 2.42%–2.82%, with an average of 2.51%, suggesting moderate maturity (Table 2; Fig. 2).

The shales of the 7th member of the Yanchang Formation in the Ordos Basin primarily contain type II organic matter. They have TOC contents of 1.6%–7.2% (average: 4.6%) and maturity of 0.8%–1.3% (average: 1.2%; Table 2; Fig. 2). Furthermore, these shales have a maximum field desorbed gas content of 0.3–3.8 m^3/t (average: 1.7 m^3/t) and high gas content. They exhibit various gas occurrence forms dominated by adsorbed gas, which accounts for above 70% of the total gas content (Du Y et al., 2020).

The shales of the 1st member of the Qingshankou Formation in the southern Songliao Basin mainly contain type I organic matter, followed by a small amount of type II organic matter. They have TOC contents of 0.32%–3.52% (average: 1.82%) and maturity of 0.81%–1.13% (average:

0.91%; Table 2; Fig. 2). Additionally, they have gas contents of 3.73–6.68 m^3/t (average: 4.88 m^3/t), as measured using isothermal adsorption experiments.

3.3. Physical properties of reservoirs

3.3.1. Porosities

The shales of the Sinian Doushantuo Formation in well Eyangye 1 in western Hubei have porosities from 0.28%–3.47% (average: 1.76%), and the organic-rich shales of the Niutitang Formation in this well have porosities from 0.09%–6.26% (average: 3.03%). The shales of the Wufeng and Longmaxi formations in the Sichuan Basin have porosities from 2.8%–7.1%, with an average of 4.65% (Dong DZ et al., 2016). The shales of the Permian Longtan Formation encountered in well Jinshacan 1 in western Guizhou have porosities from 2.0%–4.2%, averaging 3.0%. Furthermore, the shales of the Yanchang Formation in the Ordos Basin have porosities from 0.16%–5.2% (average: 2.11%), while those in the Qingshankou Formation in the southern Songliao Basin have porosities from 0.65%–5.55% (average: 1.72%) (Table 2; Fig. 2).

3.3.2. Fractures and pores

The pore spaces in shales can be divided into fractures and pores, principally including structural fractures, interlayer foliation fractures, microfractures and pores in the argillaceous matter, organic pores, and intergranular pores in rock skeletons and clay minerals (Loucks RG et al., 2012).

The pore spaces in the shales of the Sinian Doushantuo Formation in western Hubei include microcracks, dissolution pores, and organic pores. Apatite in the shales is commonly wrapped by organic matter, around which dissolution pores can be found (Fig. 3a). The organic matter is frequently filled with mineral particles. Besides, organic pores are extensive in the shales, exhibiting high connectivity but small sizes (Fig. 3b).

Pores in the shales of the Cambrian Niutitang Formation in western Hubei primarily include intergranular pores, dissolution pores, and organic pores. Clay minerals in the shales are wrapped by massive organic matter, which contains well-developed pores and exhibits a uniform distribution. Shrinkage joints are visible between organic matter and mineral particles (Fig. 3c). Pyrite framboids, with intergranular filling of organic matter, host numerous small organic matter pores (Fig. 3d).

The gas-bearing shales of the Wufeng and Longmaxi formations in the Sichuan Basin house several types of pores, including organic pores. Pores are densely distributed in massive organic matter, with sizes of mostly tens of nanometers (Fig. 3e). Occurring as intergranular minerals, pyrite framboids are filled with some organic matter (Fig. 3f).

The shales of the Permian Longtan Formation in western Guizhou host widespread organic and intergranular pores. Organic matter in the shales mostly occurs between minerals and pyrite crystals. Numerous organic pores are found, most of which have sizes of tens of nanometers (Fig. 3g). Intergranular pores in pyrite framboids are also discovered (Fig. 3h).

The shales of the Yanchang Formation in the Ordos Basin mainly develop intergranular pores, intragranular pores, and a small number of organic pores. Intergranular pores are found between clay minerals and between clay minerals and clastic particles (Fig. 3i). Organic pores, typically in a spongy shape, occur primarily inside organic matter. Moreover, they are mixed with many discrete prototype pores, which are densely distributed inside organic matter (Fig. 3j).

The shales of the Qingshankou Formation contain many types of pore spaces, including fractures, dissolution pores, interlayer fractures, intergranular pores, microfractures, and primary pores, most of which are micro/nano pores. Illite pyrite intergranular pores in the shales are primarily distributed in the argillaceous laminae of bedding-parallel and laminated mudstones (Fig. 3k), while pyrite intergranular pores in the shales are mainly found in the massive dolomitic mudstones (Fig. 3l).

3.4. Mineralogical characteristics

For the shales of the Sinian Doushantuo Formation in the well Eyangye 1 in western Hubei, their contents of brittle minerals (e.g., quartz and feldspar) range from 10.4%–50.5% (average: 31.1%), and their carbonate mineral contents vary between 20.0%–34.6% (average: 53.2%). The carbonate minerals include dolomites and a small quantity of calcites, with the total carbonate mineral content significantly higher than that of shales in other formations. Besides, the shales have clay mineral contents of 0.2%–24% (average: 15.7%) (Table 2; Fig. 4).

The shales of the Niutitang Formation in the same well have brittle mineral contents of 19.0%–76.6% (average: 54.1%), which are higher than those of shales in the Sinian Doushantuo Formation. These shales have carbonate mineral contents of 10.7%–71.9% (average: 25.9%). The carbonate minerals exhibit similar contents of dolomite and calcite, with the total carbonate mineral content significantly lower than that of shales in the Cambrian Niutitang Formation. In addition, the shales have clay mineral contents of 3.9%–25.8% (average: 14.9%), which are comparable to those of shales in the Doushantuo Formation (Table 2; Fig. 4).

The shales of the Wufeng and Longmaxi formations in the Fuling shale gas field have brittle mineral contents of 40%–85.9% (average: 62.78%), which are much higher than those of other organic-rich shales. These shales have carbonate mineral contents of 2%–22.9% (average: 7.5%), which are far lower than those of shales in other formations. Additionally, the shales have clay mineral contents of 10.8%–54%, with an average of 29.7% (Table 2; Fig. 4).

The shales of the Permian Longtan Formation in western Guizhou have brittle mineral contents of 2.2%–60.95% (average: 37.88%), which is lower than that of other organic-rich shales. They have a carbonate mineral content between 20.15%–97.8% (average: 56.48%), which is significantly higher than that of shales in other formations. Besides, these shales have clay mineral contents of 0%–53.45%, averaging 6.83% (Table 2; Fig. 4).

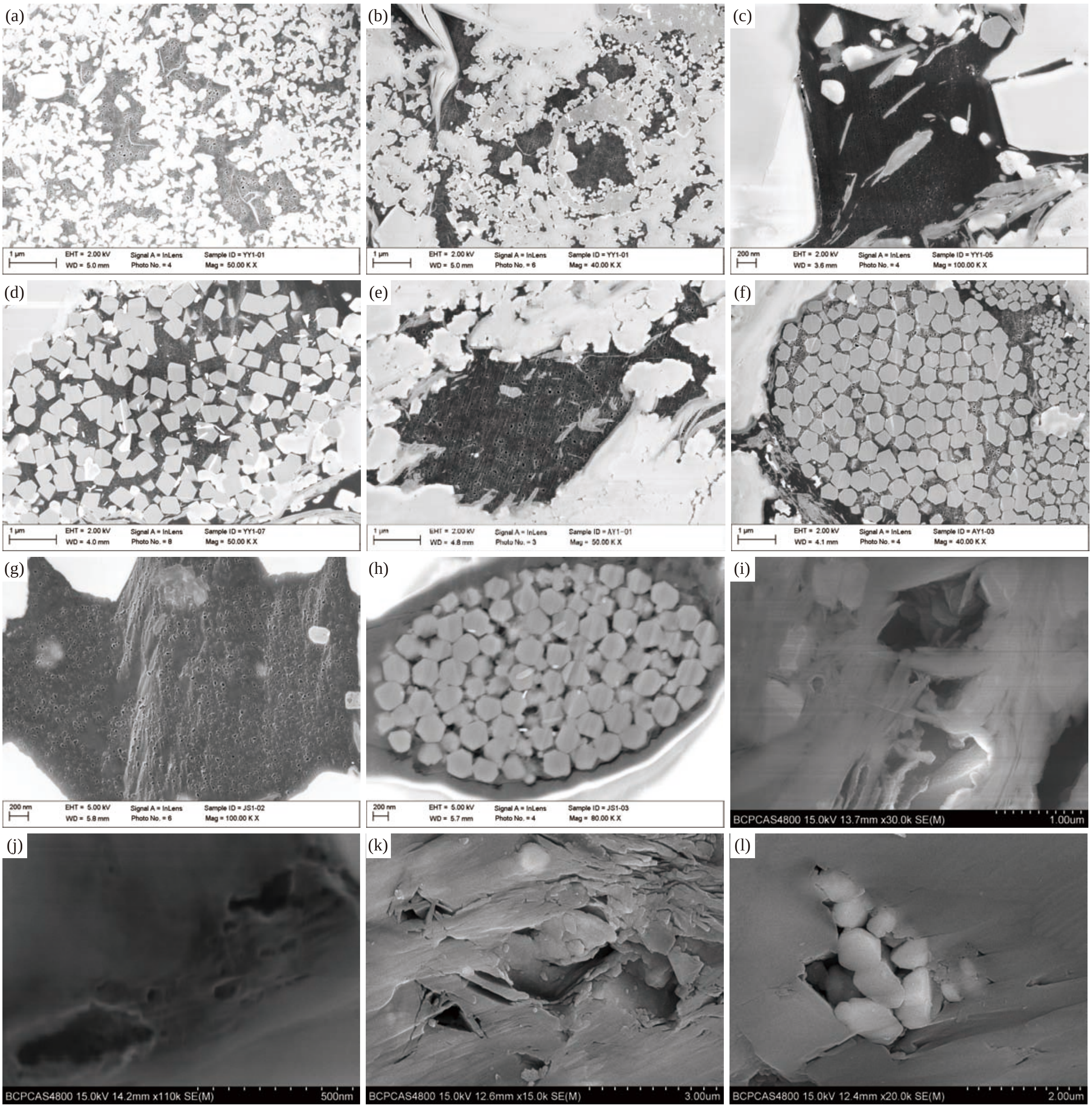

Fig. 3. SEM photos show the different pore types. a–dissolved pores in Doushantuo shale; b–organic pores in Doushantuo shale; c–shrinkage joints between organic matter and mineral particles in Niutitang shale; d–strawberry-shaped pyrite aggregates and intercrystalline filling of organic pores in organic matter in Niutitang shale; e–mass organic matter and internal organic pores in Longmaxi shale; f–strawberry-shaped pyrite aggregates and intercrystalline filling of organic pores in organic matter in Longmaxi shale; g–organic pores in Longtan shale; h–strawberry-shaped pyrite intercrystalline pores in Longtan shale; i–intergranular pores between clay minerals and detrital particles in Yanchang shale; g–spongy organic pores in Yanchang shale; k–intercrystalline pores in clay minerals in Qingshankou shale; l–intercrystalline pores in pyrite Qingshankou shale.

The shales of the Triassic Yanchang Formation in the Ordos Basin have brittle mineral contents of 12.6%–55.9% (average: 40.5%) and carbonate rock contents of 0–27.4% (average: 1.76%), both of which are significantly lower than those of shales in other formations. These shales have clay mineral contents of 31.4%–86.7% (average: 57.7%), which are generally high (Table 2; Fig. 4).

The shales of the Cretaceous Qingshankou Formation in the Songliao Basin have brittle mineral contents of 37%–68% (average: 49.2%) and carbonate rock contents of 0–26% (average: 7.73%), both of which are slightly higher than those of shales in the Triassic Yanchang Formation in Ordos Basin but lower than those of organic-rich shales of the marine facies and marine-continental transitional facies. These shales have clay mineral contents of 27%–55%, with an average of 43.1% (Table 2; Fig. 4).

4. Discussion

4.1. Effect of TOC on shale gas content

Different types of shales in several key regions have an average organic matter abundance of over 2.0%, providing a sound material basis for shale gas generation. The shales of the Triassic Yanchang Formation in the Ordos Basin exhibit the highest average TOC content of 4.6%. The shales of the Permian Longtan Formation in Western Guizhou occur in coal measure strata of the marine-continental transitional facies. Multiple sets of thin coal seams are distributed in the shale series, resulting in a high average TOC content. Furthermore, several sets of these shales are rich in organic matter, serving as a solid material basis for shale gas generation.

Organic matter, which is a primary source of shale gas, also plays an important role in shale gas accumulation and storage (Kenley TJ et al., 2008; Zou CN et al., 2010). Gas content, an important parameter used to calculate shale gas resources, can be used to determine shales ' potential for economic exploitation. In the case of the three sets of marine shale formations, there is a close positive correlation between the shale gas content of each formation and the TOC content under the same geologic setting (Fig. 5).

4.2. Thermal evolution and storage capacity of shales

Despite different locations and sedimentary facies, the several sets of organic-rich shales show gradually decreasing average degrees of thermal evolution from old to young. Among them, the Doushantuo Formation shales exhibit the highest average *R*o of 3.24% and are in the over-mature stage. The shales of the Niutitang, Wufeng, Longmaxi, and Longtan formations share similar thermal evolution degrees and are in the highly mature stage. The continental shales of the Yanchang and Qingshankou formations have low *R*o values, with averages of 1.20% and 0.91%, respectively. These shales are in the early stage of maturity.

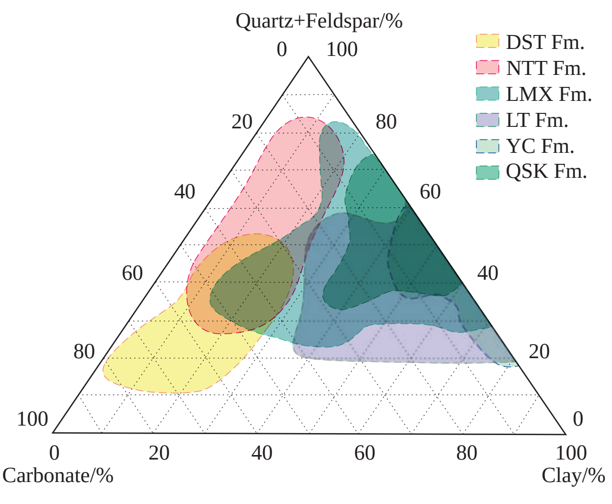

Fig. 4. Triangle diagram of the mineral content of different types of shale. The legend abbreviations are the same as in Fig. 2.

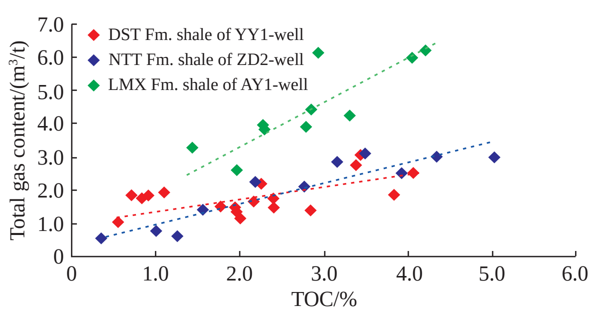

Fig. 5. Relationship between TOC and total gas content.

Source rocks begin to generate natural gas only in a certain stage of thermal evolution. Furthermore, different types of organic matter in the gas window correspond to different degrees of thermal evolution. Nevertheless, the shales of the Doushantuo, Niutitang, Wufeng, Longmaxi, and Longtan formations are in the highly mature to over-mature stage. A large quantity of natural gas has been produced and stored in different types of pore spaces in these shales, forming shale gas. The shales of the Yanchang and Qingshankou formations, which have low degrees of thermal maturity, are only in the early stage of maturity and begin to generate gas. Presently, the production capacity construction of shale gas has not been achieved for continental and marine-continental transitional shales. This might be due to the limited thermal evolution and low gas content of the shales.

The degree of thermal maturity also affects the development of organic matter pores in shales and then affects the total porosity of shales. In the case of no structural damage and sedimentary compaction, a higher degree of thermal evolution corresponds to more developed organic matter pores, which increases the total porosity of shales. In contrast, a lower degree of thermal evolution is associated with less developed organic matter pores. In this case, a large amount of liquid hydrocarbon will block the inorganic pores and a small number of organic matter pores (Curtis ME et al., 2012; Yang F et al., 2013).

As shown by the statistical analysis of the measured *R*o, porosity, and total gas content of many cores for shale gas wells in China, the total porosity of shales gradually decreases with an increase in *R*o. Specifically, the total porosity of shales decreases to below 2.0% when *R*o is over 3.6% (Fig. 6a). Furthermore, the total gas content in shales increases first and then decreases as *R*o increases, peaking when *R*o is between 2.0% to 3.0% (Fig. 6b).

Marine shales (e.g., the shales of the Niutitang Formation in Western Hubei and the Wufeng and Longmaxi formations in the Sichuan Basin) and marine-continental transitional shales (e.g., the shales of the Longtan Formation in Western Guizhou) are more favorable for shale gas enrichment. In contrast, continental strata generally show low degrees of thermal maturity. It is necessary to focus on areas with relatively high degrees of thermal evolution in shale gas survey and exploration.

The high degree of thermal maturity also has an adverse impact on shale gas enrichment. On the one hand, the shales of the stage of over-maturity cannot generate gas, showing the absence of continuous natural gas generation and supply.

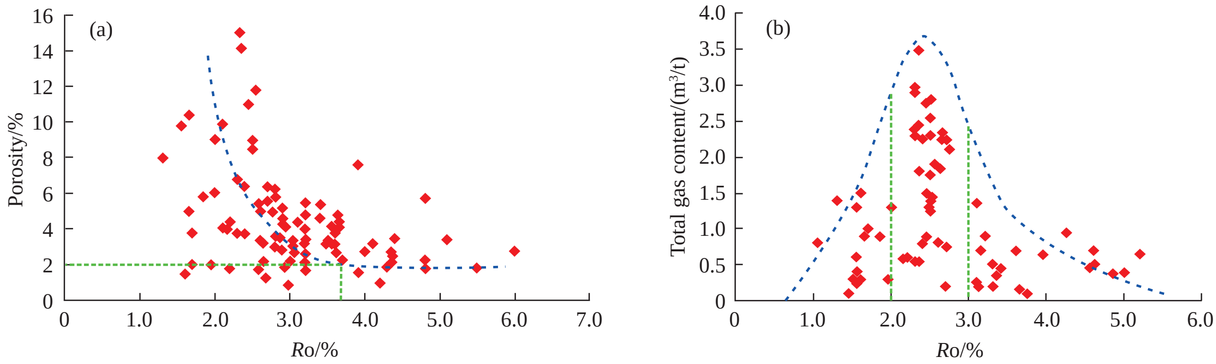

Fig. 6. Relationship of Vitrinite reflectance (*R*o) to porosity and total gas content.

Under the influence of factors such as natural gas loss and formation compaction, pores in shales are prone to collapse, resulting in the shrinkage of reservoir space. This phenomenon has been proved under a scanning electron microscope. Specifically, the shales of the Doushantuo and Niutitang formations in Western Hubei mostly contain flat organic matter pores, while those in the Wufeng and Longmaxi formations mostly hold round organic matter pores. On the other hand, previous studies indicate that the organic matter of shales begins to graphitize when *R*o exceeds 3.5% (Hou YG et al., 2021). Therefore, marine shales of the Sinian Doushantuo Formation and Cambrian Niutitang Formation generally show high degrees of thermal maturity. It is necessary to focus on areas with a relatively low degree of thermal evolution in shale gas investigation and exploration.

4.3. Porosity and shale gas storage capacity

Shale gas primarily occurs either on surfaces of organic matter and clay minerals in the form of adsorption or within micro/nano pores inside shales in a free state (Curtis JB, 2002). The porosity of shales acts as an important factor affecting the total gas content in shales.

Organic matter pores, formed by the hydrocarbon generation of organic matter, serve as an important type of pore for shale gas. Therefore, the abundance of organic matter directly affects the total porosity of shales. As revealed by the statistical analysis of the TOC and porosity data of the shales of the Niutitang, Wufeng, and Longmaxi formations in the Sichuan Basin and the shales of the Doushantuo and Niutitang formations in Western Hubei, there is a strong positive correlation between the TOC content and porosity for each set of shales. The porosity of shales increases progressively with the TOC content (Fig. 7). Comparison shows that different strata show different slopes of the TOC content *vs*. porosity relationships under the same TOC content. The shales of the Wufeng and Longmaxi formations exhibit higher porosity than those in the Doushantuo and Niutitang formations, suggesting the reservoir space of shales in the Doushantuo and Niutitang formations is also affected by other factors such as the degree of thermal evolution mentioned above. The continental shales of the Yanchang and Qingshankou formations exhibit insignificant TOC content and porosity, indicating that organic matter pores are not well developed or that they are not the major type of pore space for the two sets of shales (Fig. 8).

As shown by the statistical analysis of the porosity and total gas content of marine shales of the Wufeng and Longmaxi formations, marine-continental transitional shales of the Longtan Formation, and Jurassic continental shales of the Sichuan Basin, there is a strong positive correlation between the porosity and total gas content of the shales. In other words, the total gas content of the shales increases gradually with the porosity. Therefore, the porosity of shales directly affects their total gas content and then affects their resource potential and exploration prospect (Fig. 9).

The comparison of the porosity of shales in different strata shows that the shales of the Wufeng and Longmaxi formations exhibit the highest porosity, with an average of 4.65%. Therefore, these shales are the most favorable shale gas reservoirs, followed by the shales of the Niutitang, Longtan, Doushantuo, Yanchang, and Qingshankou formations, which have low porosity despite a certain gas storage capacity (Fig. 2). Continental and marine-continental transitional shales have lower porosity than marine shales, which may also serve as a primary reason why the production capacity construction of shale gas has not been achieved for these shales.

4.4. Brittle mineral content and shale fracability

The brittle mineral content serves as an important factor influencing the development of pores and microfractures, as well as the gas-bearing capacity and fracturing pattern. The mineral composition is critical to the exploitation of shale gas. Shales with commercial development value generally have brittle mineral contents of over 40% (Dong DZ et al., 2016).

The shales of the six sets of strata exhibit distinctly different brittle mineral contents. Among them, the shales of the Wufeng and Longmaxi formations show the highest contents of brittle minerals (e.g., quartz and feldspar), with an average of 62.78%. These shales are followed by the shales of the Niutitang, Yanchang, and Qingshankou formations. The shales of the Doushantuo shale exhibit the lowest brittle mineral content, with an average of 31.1% (Table 2).

The shales of the Wufeng and Longmaxi formations have high brittle mineral contents. For these shales, quartz serves as a primary source of organic silicon, and there is a strong positive correlation between the quartz content and the TOC content. Therefore, these shales boast favorable conditions for shale gas generation, storage, and later fracturing. Although the shales of the Doushantuo Formation have low quartz and feldspar contents, these shales have a high carbonate mineral content, with an average of 52.3%, which is higher than that of other sets of shales. The high carbonate mineral content can improve the brittleness of the shales to a certain extent. Meanwhile, more dissolution pores are easily produced in the shales under the action of organic acids in the process of diagenetic evolution, increasing the pore space of the shales.

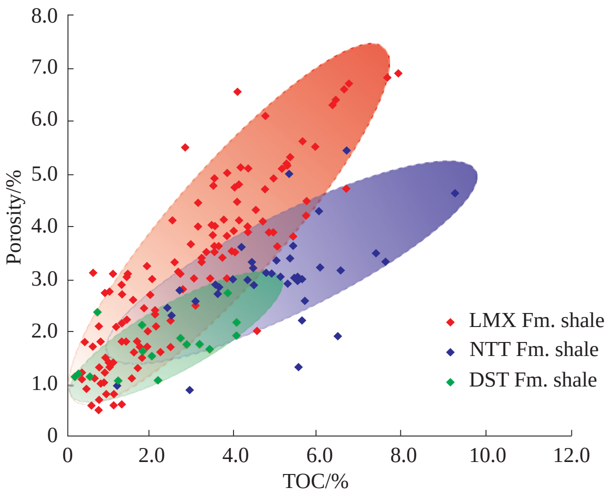

Fig. 7. Relationship between porosity and TOC. Part of the data comes from Xiao XM et al., 2015; Qiao H et al., 2018; Deng J et al., 2018.

The shales of the Longtan Formation exhibit a medium brittle mineral content since they are developed in coal measure strata. Thin interbeds of tight sandstone with different thicknesses are frequently found in the strata. For these shales, it is recommended that fracturing combined with drainage of multiple sets of lithologic strata should be employed to improve their shale gas production. Compared to marine and marine-continental transitional shales, the shales of the Yanchang and Qingshankou formations exhibit a low brittle mineral content, a high clay mineral content, and low formation pressure. These factors will affect the effect of hydraulic fracturing to varying degrees, and the CO_2 fracturing technology is more suitable for continental shale gas development (Wang XZ et al., 2014).

5. Conclusions

(i) Different types of shales in China have high organic matter content, proving that these shales enjoy a firm material basis for shale gas generation.

(ii) Marine shales of the Wufeng and Longmaxi formations have the highest porosity, thus serving as the most favorable shale gas reservoirs. These shales are followed by those in the Niutitang and Longtan formations. The shales of the Doushantuo, Yanchang, and Qingshankou formations exhibit low porosity but still have a certain gas storage capacity.

(iii) The shales of the Wufeng and Longmaxi formations have a high brittle mineral content, which is favorable for later fracturing. The shales of the Doushantuo Formation have

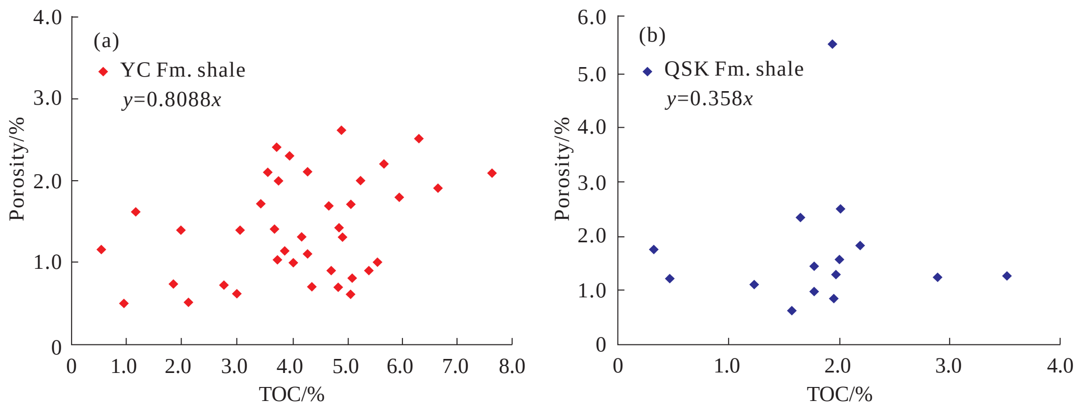

Fig. 8. Relationship between porosity and TOC. The data on Yanchang shale come from Li XJ et al., 2017.

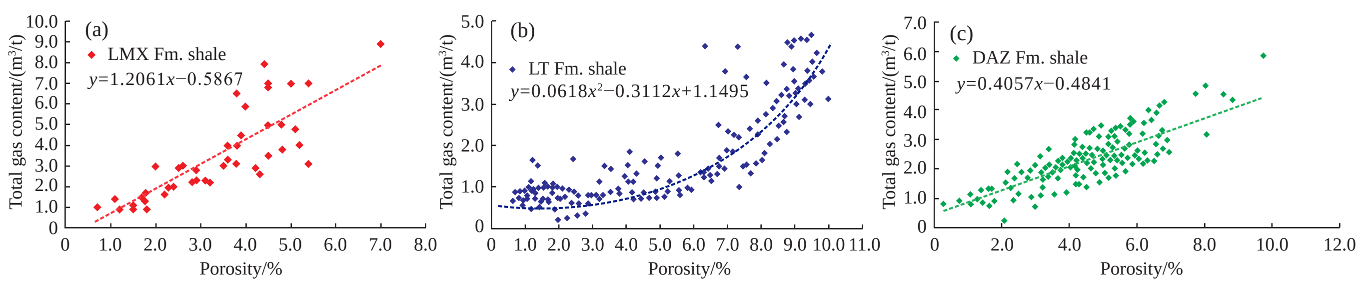

Fig. 9. Relationship between porosity and total gas content. Part of the data comes from Qiao H et al., 2018; Guo XS et al., 2016. Data from Permian and Jurassic shale were derived from log interpretation.

high carbonate mineral content, which can improve the shales ' brittleness to a certain extent. Meanwhile, more dissolution pores are easily produced in the sales under the action of organic acids in the process of diagenetic evolution, increasing the pore space of shales. For the marine-continental transitional shales, where thin interbeds of tight sandstone with different thicknesses are frequently found, it is recommended that fracturing combined with drainage of multiple sets of lithologic strata should be employed to improve their shale gas production. For continental shales, which exhibit a low brittle mineral content, a high clay mineral content, and low formation pressure, the CO_2 fracturing technology can be used for their shale gas development.

CRediT authorship contribution statement

Shu-jing Bao and Tian-xu Guo conceived the presented idea. Tian-xu Guo, Jin-tao Yin, and Wei-bin Liu carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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