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China organic-rich shale geologic features and special shale gas production issues

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ABSTRACT

The depositional environment of organic-rich shale and the related tectonic evolution in China are rather different from those in North America. In China, organic-rich shale is not only deposited in marine environment, but also in non-marine environment: marine-continental transitional environment and lacustrine environment. Through analyzing large amount of outcrops and well cores, the geologic features of organic-rich shale, including mineral composition, organic matter richness and type, and lithology stratigraphy, were analyzed, indicating very special characteristics. Meanwhile, the more complex and active tectonic movements in China lead to strong deformation and erosion of organic-rich shale, well-development of fractures and faults, and higher thermal maturity and serious heterogeneity. Co-existence of shale gas, tight sand gas, and coal bed methane (CBM) proposes a new topic: whether it is possible to co-produce these gases to reduce cost. Based on the geologic features, the primary production issues of shale gas in China were discussed with suggestions.

1. Introduction

Organic-rich shale, including mudstone and shale, was conventionally considered as source rock of hydrocarbon in sedimentary basins. Even though geologists observed natural gas in organic-rich shale long ago (e.g. Devonian Dunkirk shale in the Appalachian basin in 1982 in USA and well Wei5 in Sichuan basin in 1966 in China), the extremely low permeability (nano-level) in matrix makes it hard to produce economical oil and gas flow to the well borehole (Wang and Carr, 2012). Over the past decade, benefiting from innovative technology, horizontal drilling and hydraulic fracturing, and improved integration of geosciences and engineering, shale gas production has been increased rapidly in North America (EIA, 2012). Opportunities for increased shale gas production appear to be global. As investigated by Ministry of Land and Resources of People's Republic of China in 2012, the recoverable shale gas reserve is up to 25.08×10^{12} m^3 in the land area of China (Zhang et al., 2012a).

Organic-rich shale is not only deposited in marine environment, but also in non-marine environment: marine-continental transitional environment and continental environment (mostly lacustrine facies) in China (Zhang et al., 2008; Zou et al., 2011). Distinct from North America, marine organic-rich shale contains only 1/3 of all recoverable shale gas resource, and about 2/3 shale gas was also generated and stored in marine-continental transitional facies and continental facies (Zhang et al., 2012a). The marine shale gas reservoirs were primarily distributed in Paleozoic formations in Yangtze Platform and Tarim basin, while the continental and marine-continental transitional shale reservoirs were distributed in Mesozoic and early Cenozoic formations of basins in North China plate, basins in Northwest China and Sichuan basin. The different types of depositional environments strongly affect the lithology stratigraphy, mineral composition, and organic matter type and organic-rich shale spatial distribution. It is more difficult to produce shale gas from non-marine shale because of the higher clay content, higher ratio of free to adsorbed gas, more interlayers and more serious heterogeneity of shale gas reservoirs. As for the marine shale, even though deposited in the similar environments to North America, the more complex tectonic evolution increases the difficulties to identify the sweet spots of shale gas in China (Ju et al., 2011; Cai et al., 2013; Fang et al., 2013; Guo and Liu, 2013; Zhang et al., 2013a).

In addition, water shortage, as a serious problem in many shale gas basins in China, should be overcome through developing new

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fracturing fluid system (Hu and Xu, 2013). Severely undulating surface, pore development of infrastructure (e.g. roads), and lack of gas pipelines increase the difficulties to produce shale gas in China. It is significant to understand the geologic characteristics of organic-rich shale, their effects on shale gas production, and the special production problems of shale gas in China. Therefore, in this paper, we will analyze the primary features of shale gas reservoirs, including the spatial distribution, depositional environments, mineral composition, organic matter type, richness, and maturation. The special challenges of horizontal well and hydraulic fracturing are discussed with suggestions.

2. The major organic-rich shale in China

Reported by Oil & Gas Survey, China Geological Survey, China has drilled 129 wells related to shale gas from 2009 to 2012, including 46 vertical investigation wells, 55 vertical exploratory wells, and 28 horizontal assessment wells. The production of shale gas is about 0.25×10^{12}–0.30×10^{12} m^3 in 2012 and is up to over 2×10^{12} m^3 in 2013. These shale gas wells, conventional wells penetrating organic-rich shale, and a great number of outcrops provide the basic information to investigate the basic properties of organic-rich shale and their distribution (Fig. 1).

Organic-rich shale deposited before Pre-Cambrian was predominantly metamorphosed, except the Doushantuo shale in upper and middle Yangtze area (Table 1). Organic-rich shales of early Paleozoic were preserved in Yangtze area and Tarim basin (Fig. 1), and all of these shales were deposited in marine facies (Table 1), primarily in the shelf of carbonate platform. Qiongzhusi shale of Lower Cambrian, Wufeng shale of Upper Ordovician, and Longmaxi shale of Lower Silurian are the most promising shale gas reservoirs in South China (Table 1). The average thickness of Qiongzhusi shale is approximately 100 m, covering an area of 30×10^4–50×10^4 km^2 (Zou et al., 2011). The Wufeng–Longmaxi shale, covering most of the Yangtze area, possesses the thickness up to 120 m. Several horizontal wells targeting Qiongzhusi and Wufeng–Longmaxi shales have high initial production rate of shale gas. For example, the horizontal well Yang201-H2 is up to 43×10^4 m^3 per day at the beginning. In Tarim basin, Yuertusi shale and Saergan shale are the potential shale gas plays (Table 1). The primary characteristics of organic-rich shale in China are listed in Table 1, including thickness, total organic carbon (TOC) content, kerogen reflection (R_o), organic matter (OM) type, distribution area, and depositional environment.

During late Paleozoic, the development of organic-rich shale in North China plate became more important (Fig. 1). For example, the coal-bearing organic-rich shale in Benxi group and Taiyuan group of Carboniferous and Shanxi group of Permian were deposited in the whole North China plate, and were primarily preserved in Ordos basin, Qinshui basin, and southern North China plate (Fig. 1). Their depositional environment has been interpreted as marine-continental transitional facies. The total thickness of the three organic-rich shales ranges from 30 m to 180 m in the Ordos basin. Another marine-continental transitional organic-rich shale, Longtan shale of middle Permian, is widely distributed in Yangtze area. The Junggar basin developed three kinds of organic-rich shales during late Paleozoic, including

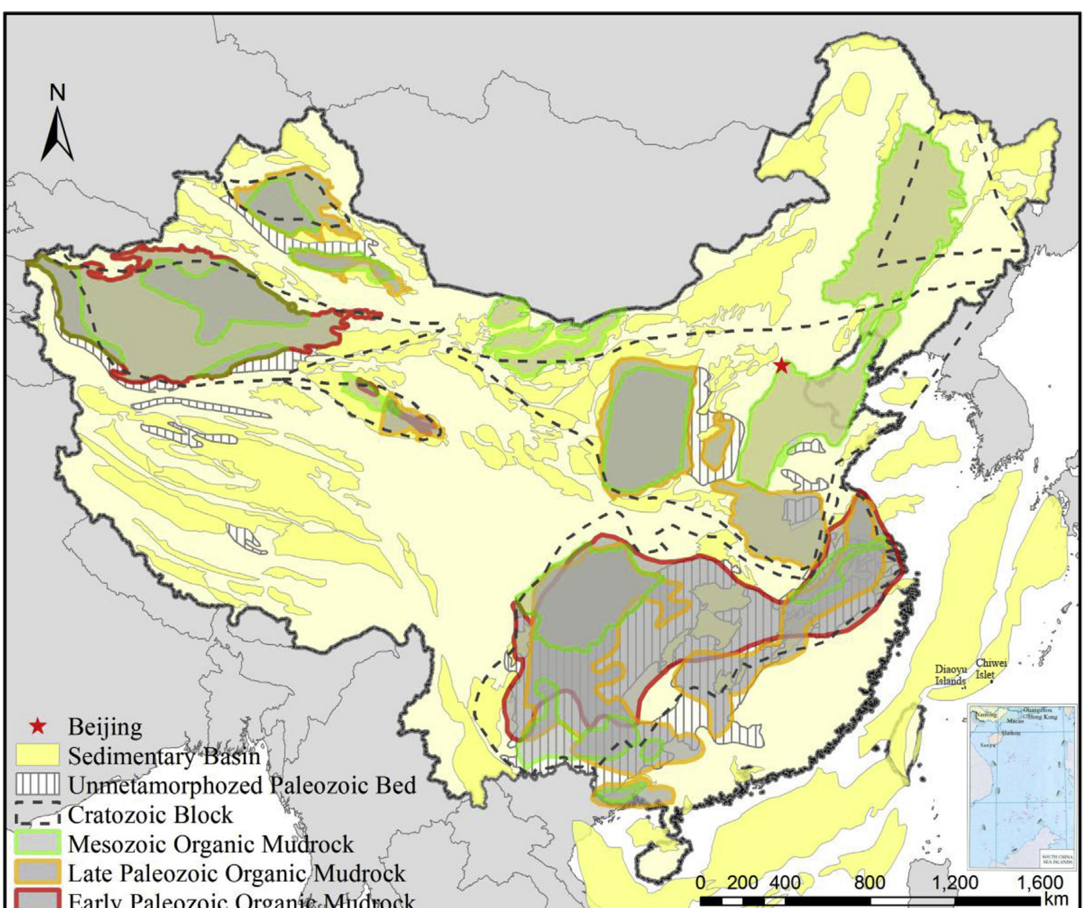

Fig. 1. The distribution of major organic-rich shale in the land area of China.

Table 1
The characteristics of organic-rich shale in China.

System period	Organic-rich shale formation	Age code	Thickness (m)	TOC content (%)	R_o	OM type	Distribution area	Environment and wells
Paleogene	Shahejie	E_3sh	10–400	0.8–16.7	0.6–3	II_1	Bohai gulf basin	LF
Cretaceous	Qing1	K_1q^1	50–500	0.4–4.5	0.5–1.5	I–II	Songliao basin	LF, δ
Jurassic	Xishanyao	J_2x	25–250	0.5–20	0.5–2.3	III	Junggar basin	LF
	Ziliujing	$J_{1-2}z$	40–180	0.8–2	0.6–1.6	I–II_2	Sichuan basin	LF, δδδ
	Badaowan	J_1b	50–350	0.6–35	0.5–2.5	III	Junggar basin	LF
	Sangonghe	J_1s	25–240	0.5–31	0.5–2.5	III	Junggar basin	LF
Triassic	Xujiahe	T_3x	80–600	1–9	1.2–3.6	III, II_2	Sichuan basin	LF, δ
	Chang7	T_3ch^7	10–45	0.3–36.2	0.6–1.2	I–II_1	Ordos basin	LF, δδδ
	Huangshanjie	T_3h	200–550	10–30	0.6–2.8	III	Tarim basin	LF
	Taliqike	T_3t	100–600	15.5–23.7	0.6–2.8	III	Tarim basin	LF
Permian	Xiazijie	P_2x	50–150	0.41–10.08	0.56–1.31	I–II_1	Junggar basin	LF
	Longtan	P_2l	20–500	0.1–12	1.3–4	III	West upper and lower Yangtze	MCTF, δ
	Fengcheng	P1f	50–300	0.47–21	0.54–1.41	I–II_1	Junggar basin	LF
	Shanxi	P_1sh	10–50	0.5–31	0.6–3.4	III	North China plate	MCTF
Carboniferous	Taiyuan	C_3t	30–90	0.5–36.8	0.6–3.4	III	North China plate	MCTF
	Benxi	C_2b	0–40	0.5–25	0.6–3.4	III	North China plate	MCTF
	Dishuiquan	C_1d	120–300	0.17–26.76	1.6–2.6	III	Junggar basin	MCTF
	Datang	C_1d	50–150	–	–	–	South upper Yangtze	MF
Devonian	Luofu	D_2l	600–1113	0.53–12	0.99–2.03	I–II	South upper Yangtze	MF
Silurian	Longmaxi	S_1l	0–200	0.41–8.28	1.5–3.6	I, II_1	South Yangtze area	MF, δδδ
Ordovician	Wufeng	O_3w	0–250	0.31–7.51	1.41–3.2	I	Lower Yangtze and south upper Yangtze	MF, δδ
	Pingliang	O_2p	50–392	0.10–2.17	0.57–1.5	I–II	Ordos basin	MF
	Dachengsi	O_1d	20–225	0.42–6	1.7–4.6	I–II	Sichuan basin	MF
	Saergan	O_1s	0–160	0.61–4.65	1.2–4.6	I–II	Tarim basin	MF
Cambrian	Qiongzhusi	ε_1q	20–465	0.35–5.5	1.28–5.2	I	Upper and middle Yangtze, lower Yangtze	MF, δδδ
	Yuertusi	ε_1y	0–200	0.5–14.2	1.2–5	I–II	Tarim basin	MF
Sinian	Doushantuo	Z_2d	10–233	0.58–12	2–4.6	I	Upper and middle Yangtze	MF

Note: Most data of thickness, TOC content, and R_o are modified from Wang et al. (2008), Zou et al. (2011) and Wang and Carr (2012); I–II means I and II, while I, II means I is dominant and II is secondary; in the last column, the relevant depositional environments include marine facies (MF), marine-continental transitional facies (MCTF), and lacustrine facies (LF); δ indicates that only parametric shale wells, mostly shallow, are drilled; δδ indicates exploratory wells are drilled; and δδδ means production wells are drilled and are producing shale gas.

marine-continental transitional Dishuiquan shale with thickness of 120–300 m, lacustrine Fengcheng shale with thickness of 50–300 m, and lacustrine Xiazijie shale (Table 1). Two marine shales, Luofu shale and Datang shale, were mainly deposited during middle Devonian and early Carboniferous in southern upper Yangtze area (Fig. 1).

No marine organic-rich shale was deposited in the land area of China during Mesozoic. Another typical feature is that rift basins in Northeast China generally developed extremely thick organic-rich shale in lacustrine facies, which is rather distinct from marine organic-rich shale in North America. For example, the Shahejie shale in Bohai Gulf basin and Qing1 shale in Songliao basin are quite thick, but the organic-rich zones usually cover a relatively small area in the deep fault blocks. In the Junggar basin and Tarim basin, organic-rich shale typically co-existed with coals and fine shaly sandstone, such as the Sangonghe shale, Badaowan shale, and Xishanyao shale of Jurassic and Taliqike shale and Huangshanjie shale of Triassic (Table 1 and Fig. 1). This kind of organic-rich shale is primarily deposited in the deep depressions of the basins. Finally but most importantly, in the stable blocks (Sichuan basin and Ordos basin), two organic-rich shales, Ziliujing shale and Chang7 shale, have produced shale gas with gas liquids, showing good perspectives as shale gas play.

3. Primary geologic features of organic-rich shale in China

3.1. Depositional model of organic-rich shale

When organic-rich shale was studied as source rock, the organic richness observed in organic-rich shale has been explained by two fundamental ideas: preservation of organic matters as the main factor (Demaison and Moore, 1980; Ettensohn and Barron, 1981) and production of organic matters (Pedersen and Calvert, 1990). To date, most depositional models for organic-rich shale (black shale) combine both preservation and productivity of organic matters. Meanwhile, especially for the shale gas reservoirs, the functions of sediment settling and dilution were emphasized. In fact, deposition and accumulation of organic-rich shale are a complex process controlled by the interaction of terrigenous sediment settling rate, sediment dilution, organic matter productivity, and organic matter preservation and decomposition (Sageman et al., 2003; Arthur and Sageman, 2005; Aplin and Macquaker, 2011; Wang and Carr, 2013).

In Fig. 2, Wang and Carr (2013) summarized three controlling factors on the deposition of marine organic-rich shale in foreland basin: sediment dilution, organic matter productivity, and preservation. Even though this model was developed initially for marine shale in foreland basin, the fundamental ideas also work for all the other depositional environments. Of course, the contribution and effects of each factor could be different in marine and continental environments. The size and spatial distribution of water body and the distance of basin center to sediment source are very distinct between open ocean, protected sea, large lack within craton, and small rift lack basin. Therefore, the effects of sediment dilution, organic matter productivity, and preservation vary in different sedimentary settings, and consequently form different geologic features of organic-rich shale.

In the Yangtze platform, the marine organic-rich shale was deposited in the large area of the protected sea, especially the shelf of carbonate platform (Fig. 3). The local depressions around the shelf were the preferred areas for the deposition of Qiongzhusi

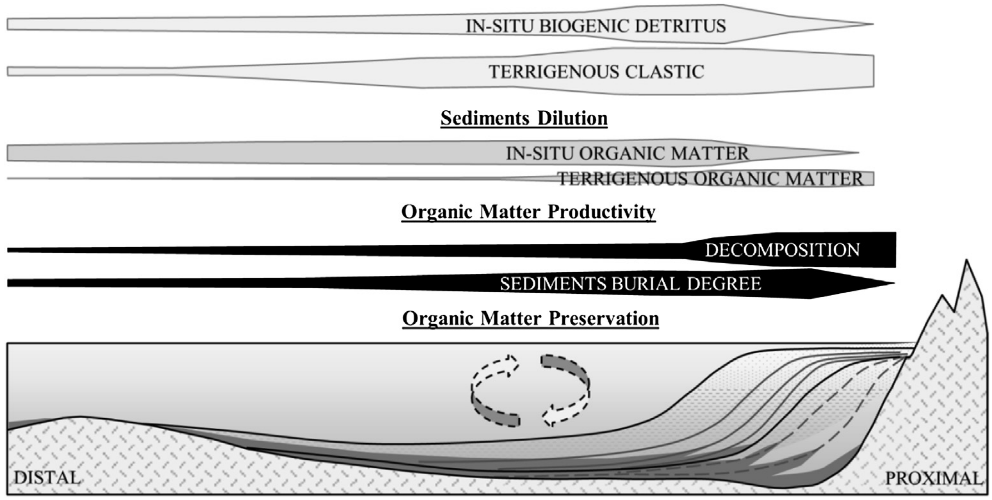

Fig. 2. Three controlling factors and their contribution to the deposition of organic-rich shale (modified after Wang and Carr (2013)). This conceptual cross-section was perpendicular to shoreline of foreland basin or lake basin.

shale and Wufeng–Longmaxi shale (Figs. 3 and 4). Distinct from North America, there existed several local depressions in Yangtze platform due to the differential subsidence and uplift. Therefore, it is more complex to identify the distribution of organic-rich shale. The relatively small water body size in depression and rifted lack basin obviously limited the development of organic-rich shale, which was generally deposited in the center of lack basins (Figs. 5 and 6). As for lacustrine organic-rich shale, the dilution of sediments is more serious in decreasing the content of organic matter. The coal-bearing organic-rich shale of marine-continental transitional facies is primarily deposited in littoral swap, including Longtan shale in Yangtze area (Fig. 7) and Benxi–Taiyuan–Shanxi shale in North China plate (Table 1).

3.2. Comparison among marine, marine-continental transitional, and lacustrine shale

The depositional environments have a significant influence on the geologic features of organic-rich shale. Firstly, the lithology stratigraphy is quite different. The marine organic-rich shale usually overlies limestone and underlies gray shale (low TOC) with a few very fine siltstones. Meanwhile, thin limestone beds are common in marine organic-rich shale (Fig. 8a). The most organic-rich zone is typically located in the lower part of the shale formation. For the marine-continental transitional organic-rich shale, the thickness of single layer is very thin but the amount of layers is large. The frequent alternation of organic-rich shale, thin limestone, coal, gray shale, siltstone, and fine sandstone is the most notable feature of transitional organic-rich shale (Fig. 8b). The most organic-rich part is close to the coal for transitional shale. Two types of lack basins exist for depositing lacustrine organic-rich shale: the depression lake basin and rift lake basin. The lithology stratigraphy in depression lake basin (Fig. 8c) is similar with the marine-continental transitional organic-rich shale, except that the distribution area of organic-rich shale is smaller. However, for the lacustrine deposited in rift lack basin, the lithology stratigraphy is rather different from all the other organic-rich shale (Fig. 8d), which is interbedded with gray shale, siltstone, and sandstone.

Another important difference is the mineral composition and organic matter richness and type. To investigate the differences among three kinds of shales, we have collected nearly 60 sets of data about mineral composition and organic matter richness and type from more than 2500 articles and theses (Tables 1 and 2). Meanwhile, parts of the data in Huainan–Huaibei coal field and northwestern Jiangxi Province were tested experimentally by us. Totally, 756 samples were used to analyze the features of mineral composition of organic-rich shale, including 599 data for marine organic-rich shale, 44 for transitional organic-rich shale, and 113 for lacustrine organic-rich shale (Table 2). In addition, nearly half of

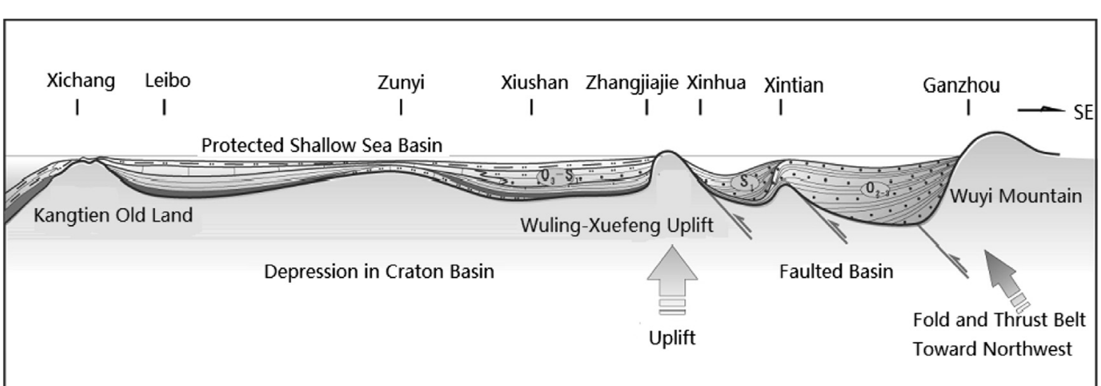

Fig. 3. The marine shale depositional environment in upper Yangtze area of Southwest China (Zhang et al., 2013b).

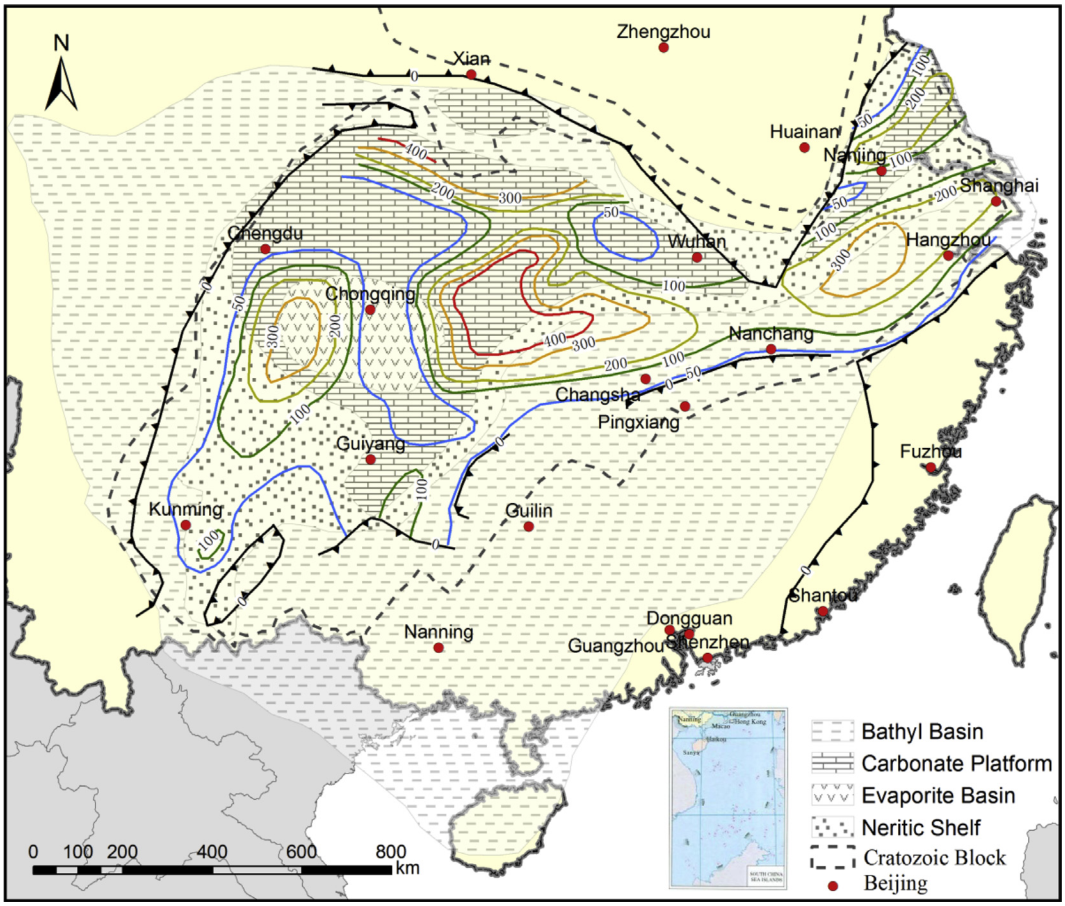

Fig. 4. The paleo-environment in early Cambrian (modified from Wang and Cai (2007)) and the isopach map of Qiongzhusi shale in the Yangtze area. The unit of isopach is in meter.

the data were from outcrop samples, which may result in the underestimation of carbonate minerals and pyrite. Other basic information about data location distribution and shale formations is summarized in Table 2.

All the 756 data concerning mineral composition of organic-rich shale were projected into the ternary plot for analysis (Fig. 9a). More than 90% of the samples are located in the area of carbonate content less than 20%, and about 2% samples contain carbonate minerals over 60%. The average content of silica minerals in all the data is 46.6%, and 36.8% for clay minerals and 12.7% for carbonate minerals. The comparison among the different depositional environments (Fig. 9b–d) indicates that: (1) marine organic-rich shale contains more carbonate minerals and limestone interlayers could be often observed; (2) silica minerals (including quartz and feldspar) in marine organic-rich shale are more than these in lacustrine organic-rich shale, and consequently the brittleness index is higher in marine organic-rich shale; and (3) the content of pyrite in marine organic-rich shale is higher than that in other two facies, especially the transitional facies, which possibly indicates the higher reduction index in marine facies. In terms of the clay mineral content (Fig. 10), illite and mixed I/S (illite and smecite) are the primary clay minerals in marine and lacustrine organic-rich shale while mixed I/S and kaolinite are dominant in marine-continental transitional shale. In addition, the content of smectite is relatively high in lacustrine organic-rich shale (Fig. 10). The TOC content in lacustrine and transitional organic-rich shale is higher than that in marine organic-rich shale in China (Table 1). Due to the TOC content reflecting the residual total organic matters in shale,

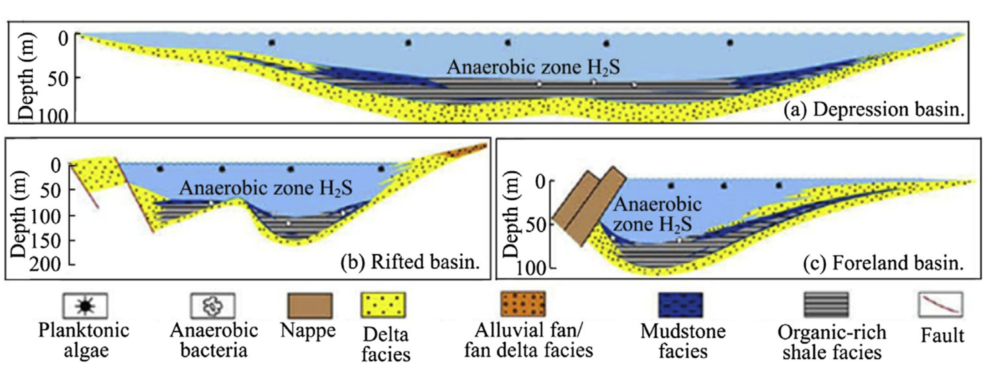

Fig. 5. The depositional model of lacustrine organic-rich shale in China (after Zou et al. (2013)).

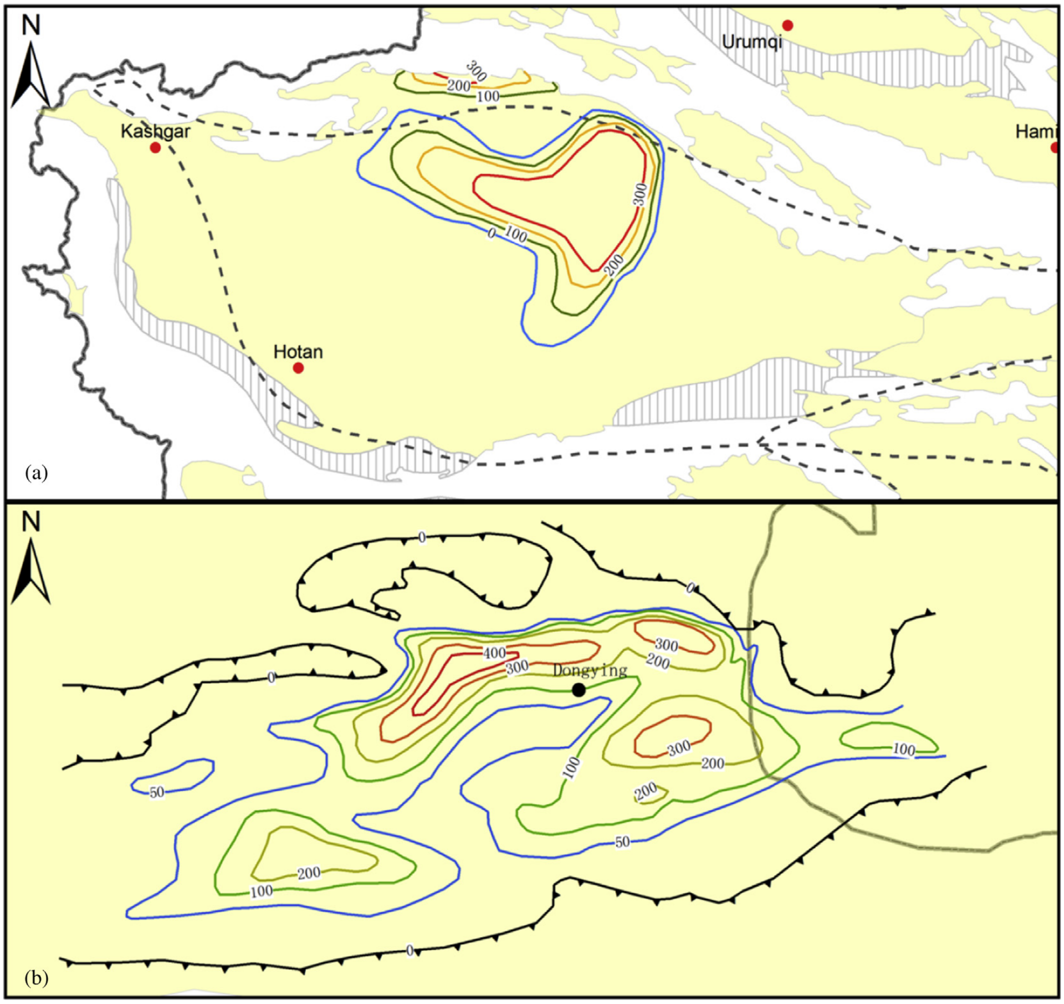

Fig. 6. The isopach map of Triassic organic-rich shale in the Tarim basin (a) and the 4th member of Shahejia shale in the Dongying depression (b). The data for isopach map is modified from Zeng et al. (2013) (a) and Zhang et al. (2012b) (b). The unit of isopach is in meter.

the higher thermal maturity in marine organic-rich shale may decrease the TOC content more. But, we believe that higher TOC content in non-marine organic-rich shale is a typical feature in China. The types I and II of kerogen are predominant for organic-rich shale deposited in marine basin and rifted lake basin, while type III of kerogen becomes more important in organic-rich shale deposited in marine-continental transitional environment and depression lake basin (Table 1).

3.3. Organic-rich shale erosion by tectonic evolution

As the depositional environments control the original geologic features of organic-rich shale (e.g. shale composition, organic matter, and distribution), tectonic evolution is the following factor, which varies these original geologic features. This is extremely important in China. Compared to North America, China has suffered from complex and active tectonic movements from Pre-Cambrian. As a unit, the basement and overlying strata were uplifted or subsided together except the orogenic belt in North America, such as the Appalachian basin. However, the basements of China were composed of several discrete land masses (Fig. 1), resulting in the differential uplift seriously. Many organic-rich shales, especially the Paleozoic organic-rich shale in Yangtze area and Southeast China, have been explored into the air or eroded totally. For example, the Qiongzhusi shale has been eroded in the south Yangtze area and Southeast China (Figs. 4 and 11), and outcrops of Qiongzhusi shale are common around the Sichuan basin. The erosion of Longtan shale is more serious in South China (Fig. 6). Therefore, as geologists stressed on depositional model of organic-rich shale in North America, geologists in China have to pay their attention to the structural features in potential shale gas plays.

Contrast to erosion, the differential uplift also leads to the large increase of burial depth of organic shale in the depression belts. For example, the deepest Qiongzhusi shale is up to over 5000 m, which is a big challenge for hydraulic fracturing. According to the experience in North America, the burial depth of 1500–3000 m is considered as a suitable target for shale gas reservoirs. The large burial depth not only increases the cost of drilling and the difficulties of fracturing, but also improves the thermal maturity of organic matter.

3.4. Detachment structure and deformation of organic-rich shale

According to the observation of outcrops and well cores, fractures were well-developed in the organic-rich shale, especially the marine organic-rich shale in Yangtze area (Fig. 12). The multiple stages of tectonic movements have resulted in the fractures crossing with each other (Fig. 11a–c). The shale has been

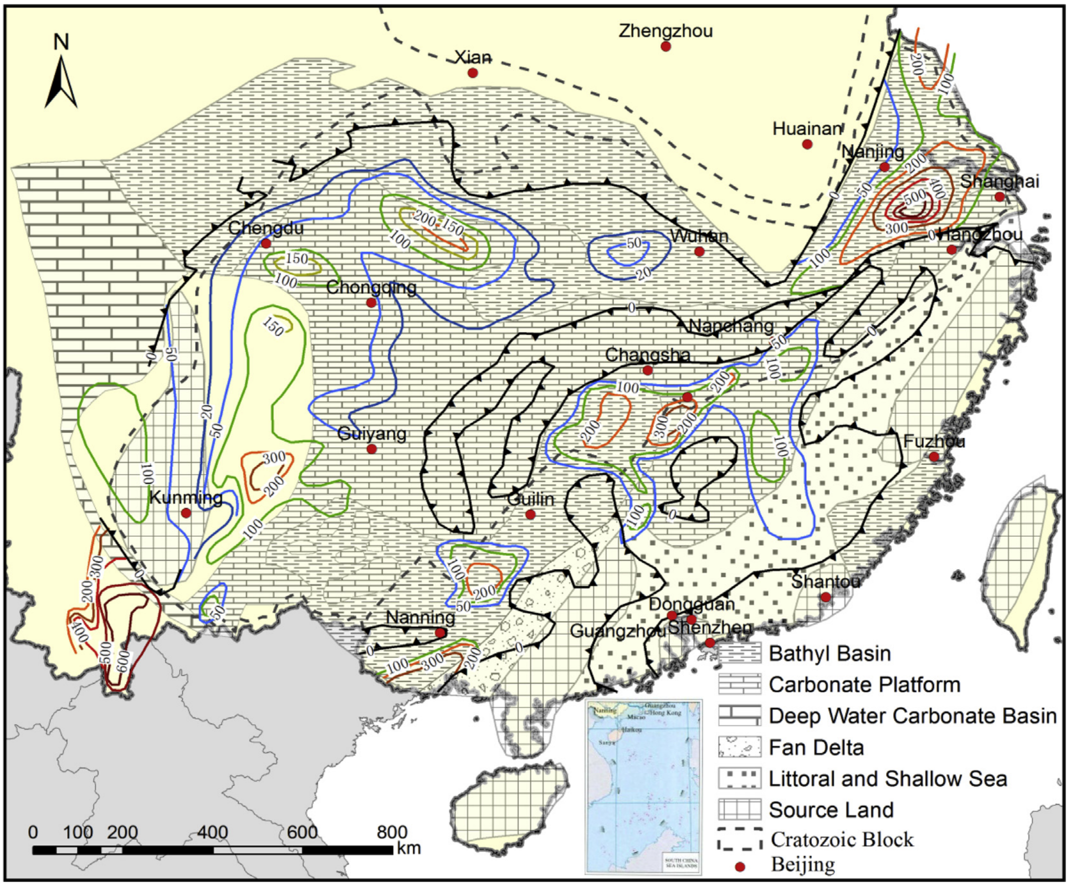

Fig. 7. The paleo-environment in early Cambrian (modified from Wang and Cai (2007)) and the isopach map of Longtan shale in the Yangtze area. The unit of isopach is in meter.

broken into many small parts, which is not good news for hydraulic fracturing and shale gas preservation. Most of these fractures have been filled with calcites primarily and quartz secondarily. These fractures are predominantly related to reverse faults and thrust faults (Fig. 11). Detachment structure was common in organic-rich shale and also caused strong deformation of organic-rich shale, which is the soft rock underground compared with limestone and sandstone. In coal-bearing organic-rich shale, besides tectonic deformation, dehydration of shale, due to exploration into the surface directly, also formed many fractures. Based on the thin sections of marine-continental transitional organic-rich shale from Huainan–Huaibei coal fields, shrink fractures were well-developed (Fig. 13). Large portion of these fractures were filled with organic matters while others were open or filled with calcite.

3.5. Thermal maturity and in-situ stress of organic-rich shale

Another effect of complex tectonic evolution is that the variation of thermal maturity of organic matter is large for different shale in different basins, even the same shales in different structural units in China. Especially for the marine organic-rich shale in Yangtze area, R_o varies from 1.5% to 5.0% (Table 1). In most area, the R_o of marine organic-rich shale is over 2.5%, which is much higher than that in North America and lacustrine organic-rich shale in China. However, for the lacustrine organic-rich shale, the thermal maturity is relatively low and, for a few organic-rich shales, the highest R_o is just above gas window (e.g. Chang7 shale in Ordos). In fact, shale oil or gas liquid in these low maturity shales, including Chang7, Shahejie, and Qing1 shale, is more important. Affected by the tectonic evolution, the in-situ stress of shale formation is relatively high in the area with large burial depth and close to the orogenic belt. Meanwhile, due to the well-developed faults and variations of fault direction, it is more difficult to evaluate the in-situ stress in the Yangtze area than that in North America and North China plate and basins in the West China.

3.6. Co-existence of shale gas, tight sand gas, and coal bed methane

In the non-marine organic-rich shale, especially the coal-bearing strata, organic-rich shale is typically interlayered with thin coal, siltstone, and fine sandstone. Organic-rich shale and coal are the source rock and gas reservoir, while siltstone and fine sandstone store parts of the gas migrating out from organic-rich shale and coal (Fig. 8b and c). Therefore, provided the reservoir with a good accumulation condition and a good preservation, shale gas, tight sand gas, and coal bed methane (CBM) co-exist with each other in many coal-bearing strata. The coal-bearing strata are widely distributed in most sedimentary basins in China. With the wide distribution of coal (accounting for about 80% of energy consumption in China), this kind of lithology stratigraphy is very significant in China. According to the investigation by Ministry of Land and Resources of People's Republic of China in 2012, the shale gas in coal-bearing strata could be up to half of total recoverable shale gas in China (non-marine shale gas is about 2/3). Due to the relatively small thickness of each single layer and the frequent alternation of organic-rich shale, coal, siltstone, and fine sandstone, it is non-commercial to produce each of these unconventional gases individually. The joint development of shale gas and CBM or shale gas and tight sand gas or all together could be a good

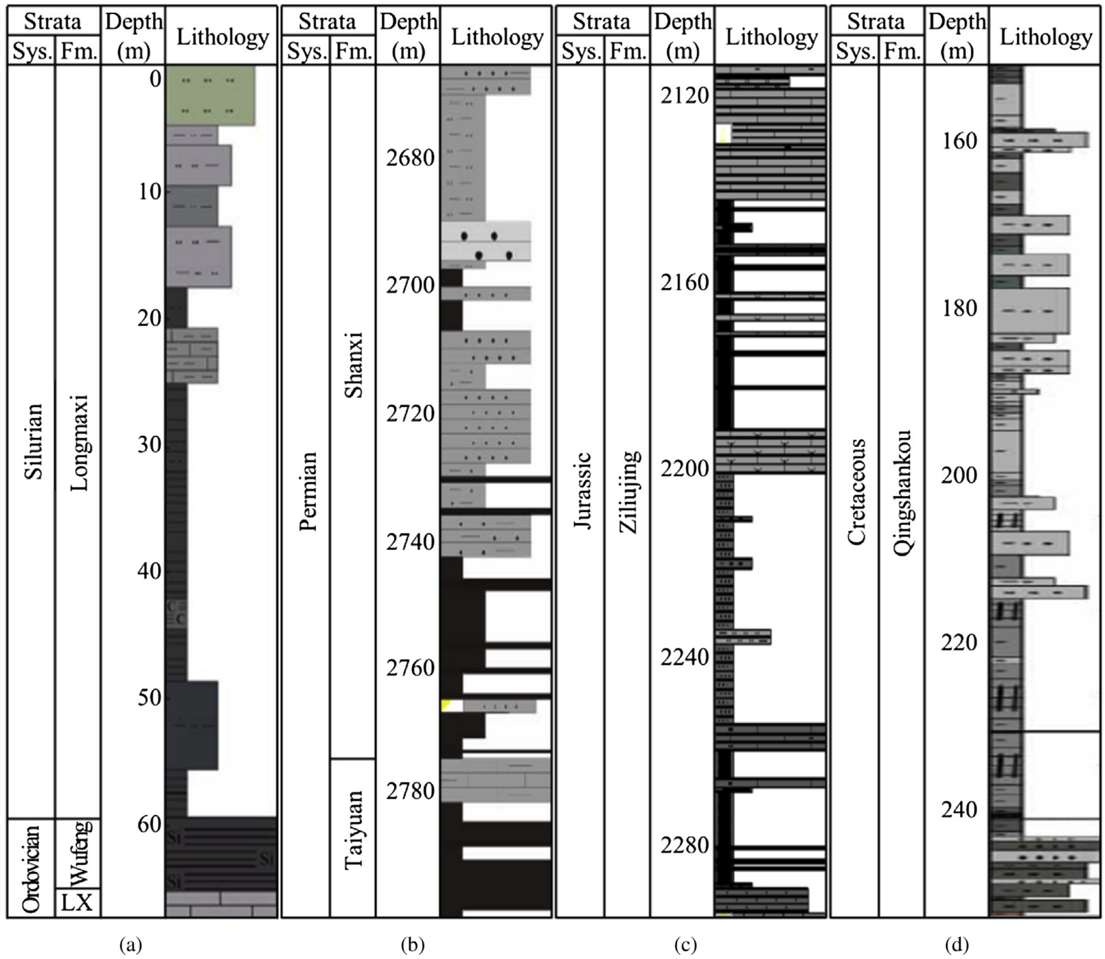

Fig. 8. Lithology section of organic-rich shale formations in wells and outcrops. (a) Marine shale (modified from Liang et al. (2012)). (b) Marine-continental transitional shale (modified from Gong et al. (2013)). (c) Lacustrine shale in depression basin (modified from Ma (2013)). (d) Lacustrine shale in rift basin (modified from Liu et al. (2012)).

opportunity to effectively develop and utilize these unconventional gases in coal-bearing strata.

4. Special issues of shale gas production in China

Shale gas is unprecedented and inspiring for people especially for China such a country with a higher population, while there are many special issues existed in.

4.1. Complex tectonic evolution

China has experienced complex tectonic evolution compared to North America. The organic-rich shale in North America is mainly distributed in the early Paleozoic and Mesozoic and predominantly deposited in marine environments. Meanwhile, the geologic structure is relatively stable in North America. However, the basement of China is composed of several discrete paleo-land masses and consequently differential uplift and subsidence are serious. More importantly, the marine organic-rich shales, such as Qiongzhusi shale and Longmaxi shale, were developed in early Paleozoic, which suffered from multiple tectonic movements, such as Indosinian movement, Yanshan movement, Himalayan orogeny, and so on (Ju et al., 2005). The differences among different structural units in Yangtze area are obvious, including burial depth, erosion and deformation, faults and fractures, in-situ stress, and thermal maturity. The strong heterogeneity of organic-rich shale in China related to complex tectonic evolution has markedly increased the difficulties of shale gas exploration. Furthermore, all

Table 2
The basic information of collected data concerning mineral composition of potential shale gas reservoirs.

Total	Depositional facies			Data source		Data location			
	Marine	Transitional	Lacustrine	Outcrop	Well	Yangtze	Ordos basin	Bohai gulf basin	Others
756	599	44	113	354	402	599	64	51	42

Total	Organic-rich shale formation								
	Longmaxi	Qiongzhusi	Dalong	Longtan	Benxi–Taiyuan–Shanxi	Shahejie	Chang7	Qingshankou	Others
756	343	129	54	11	33	51	31	12	92

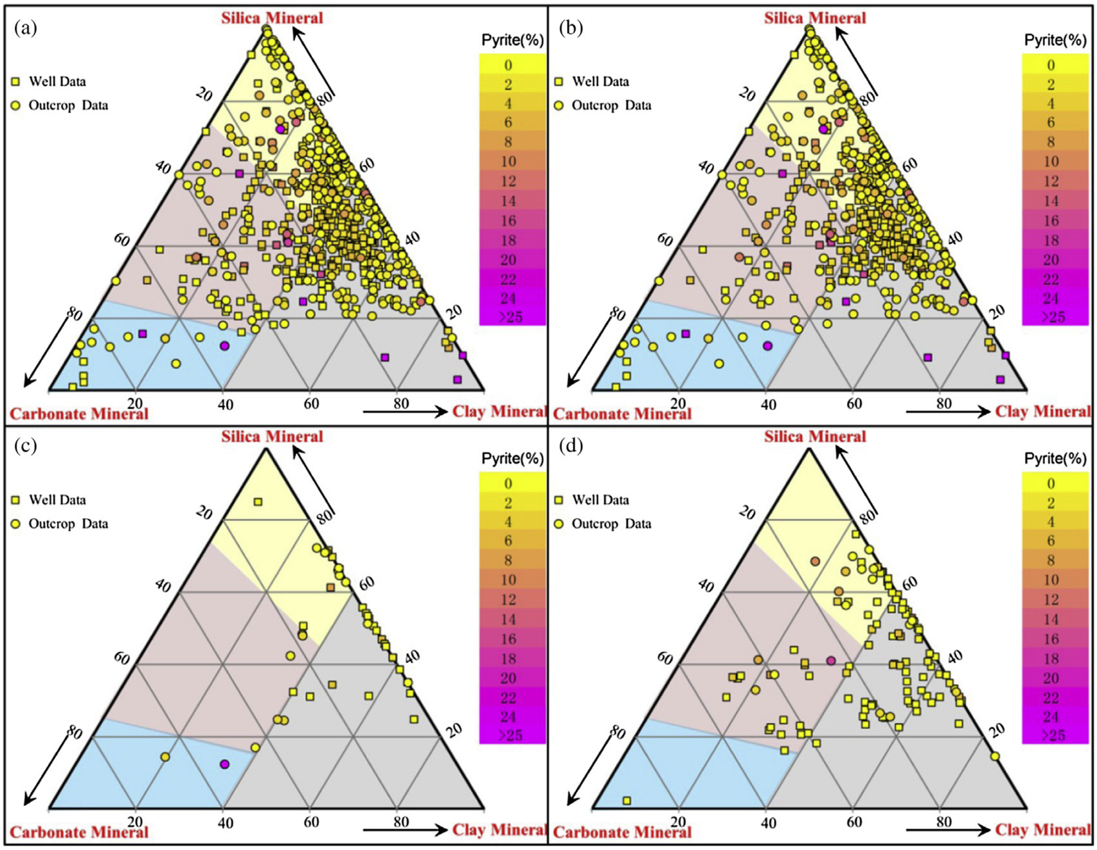

Fig. 9. Mineral composition features of organic-rich shale deposited in different environments in China. (a) All data together. (b) Marine organic-rich shale. (c) Marine-continental transitional organic-rich shale. (d) Lacustrine organic-rich shale.

these features are not beneficial to the effective design of horizontal well and hydraulic fracturing, and will increase the associated cost.

4.2. Fracturing of non-marine shale

To date, most experiences of hydraulic fracturing of organic-rich shale are from marine shale in North America. It is questionable to use them directly to the stimulation of organic-rich shale in China, especially the non-marine shale. To non-marine shale, there have very higher clay contents, which are water-sensitive especially for kaolinite and smectite, which is detrimental to hydro-fracture. To solve these issues, CO_2 is considered as a fracturing fluid during the reservoir stimulation. In addition, thousands of oil and gas technology service companies in USA can provide professional design and suggestion concerning the local issues of hydraulic fracturing. However, professional oil and gas technology enterprises are lacked in China, which also increases the risk and cost of stimulation.

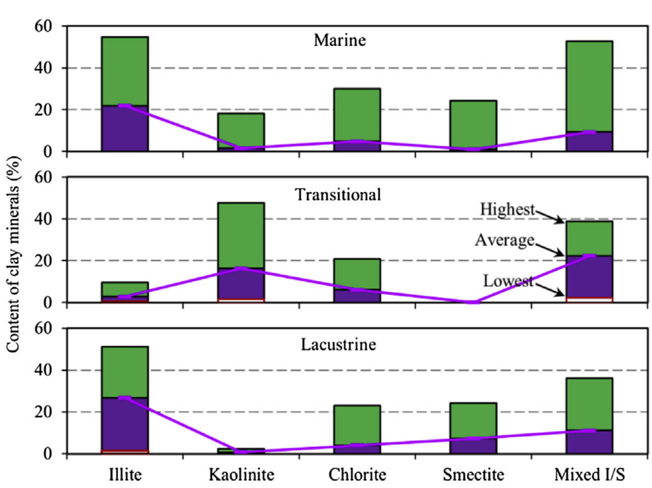

Fig. 10. The highest, average, and lowest contents of clay minerals in different depositional environments in China.

4.3. Joint development of multiple unconventional gases

China is the first coal production country in the world, and the coal resource accounts for 37% worldwide. The Ordos basin is known as a large coal-bearing basin, which possesses greater than 500 billion tons of coal resource. In the coal-bearing strata, organic-rich shale is typically interlayered with coal and fine sandstone, especially in marine-continental transitional facies and lacustrine facies in depression lake basin. In coal mining fields, the organic-rich shale often overlies or underlies the coal beds. The co-existence of shale gas and CBM is common in the coal-bearing strata (Chen et al., 2011), such as the Longtan group in Yangtze region (Fig. 7) and Benxi–Taiyuan–Shanxi group in North China plate. In addition, the thin sandstone will store gases migrating out from coal and shale gas as the fine sandstone interlayered with coal and organic-rich mudrock. Due to the small thickness of each layer of organic-rich mudrock, or coal, or fine sandstone, it is non-commercial to produce these unconventional gas individually. Joint production of the three unconventional gases is a good idea to reduce cost and improve the efficiency. Therefore, combined research and development is the nice choice for shale gas and CBM

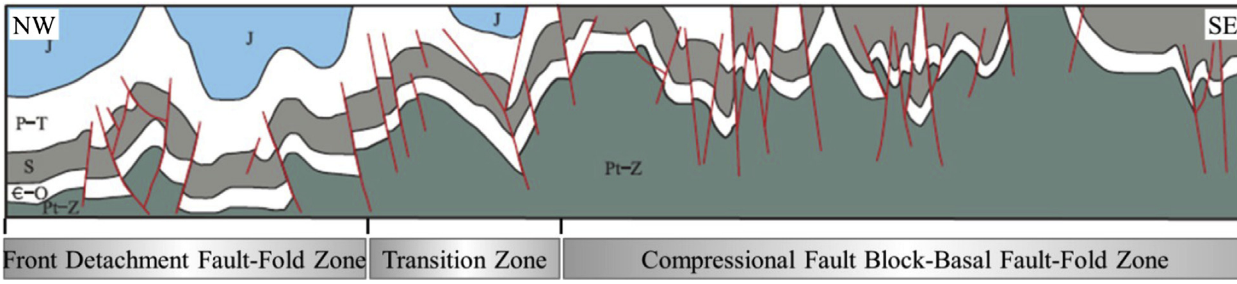

Fig. 11. Structural profile of eastern Sichuan basin and western Hubei-Hunan area (modified from Ma et al. (2012)).

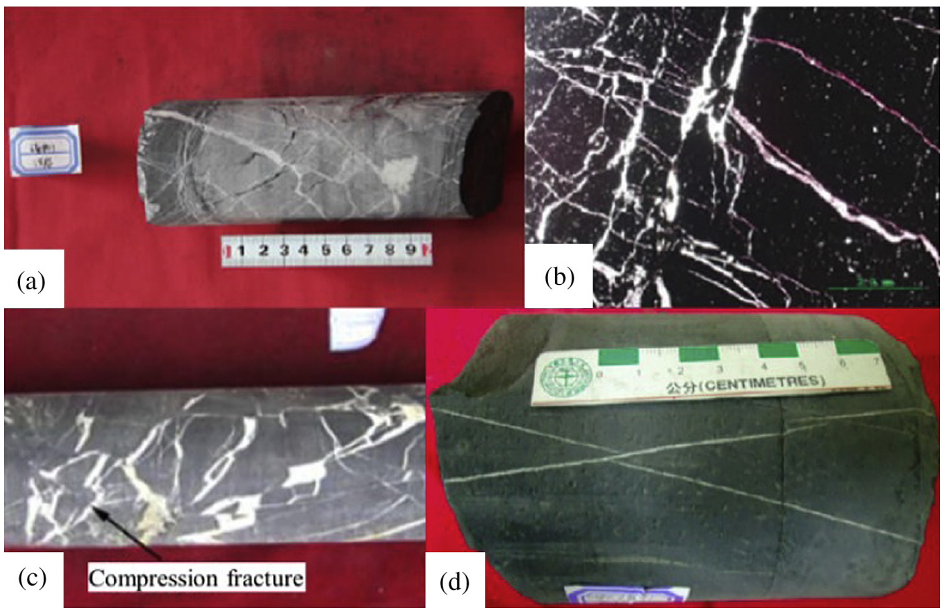

Fig. 12. Well-developed fractures observed in the well cores of marine organic-rich shale in Yangtze area, China. (a) Well Keye1 (modified from Xie et al. (2013)). (b) Well Changxin1 (modified from Chen et al. (2013)). (c) Well Yuye1 (modified from Long et al. (2012)). (d) Well Cenye1 (modified from Zhao (2013)).

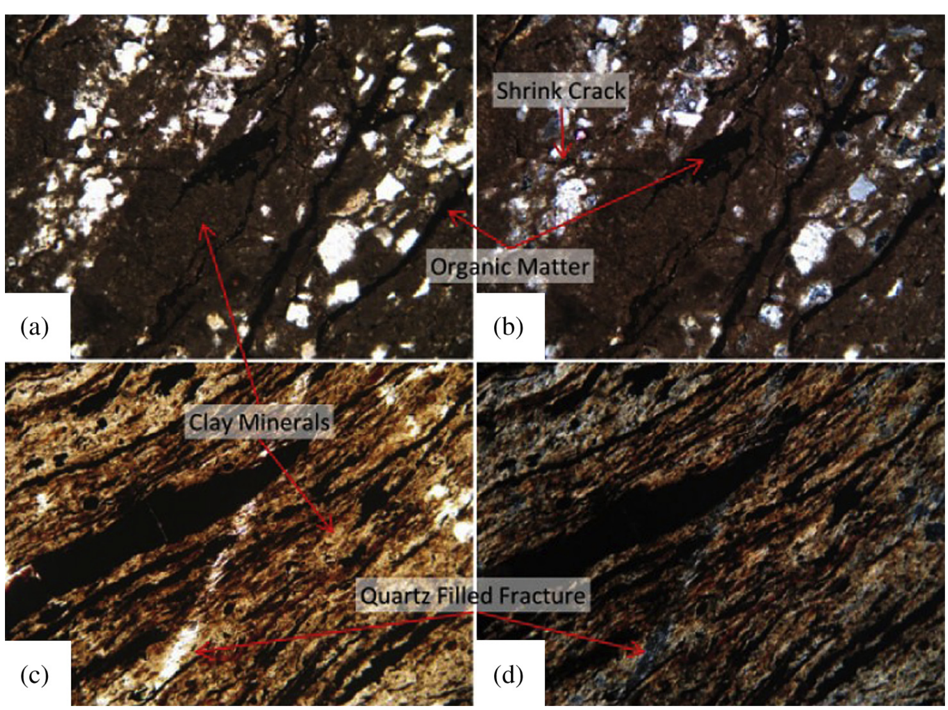

Fig. 13. Thin section images of late Paleozoic coal-bearing shale in coal mining area of southeastern North China plate. (a) Sample HB-LH-2 (PP, 100×); (b) Sample HB-LH-2 (CP, 100×); (c) Sample HB-LL-1 (PP, 100×); and (d) HB-LL-1 (CP, 100×). CP: crossed polarized light; PP: plane polarized light.

even other natural gas in some sedimentary environment. These technologies can be used as a long-term view.

4.4. Water issue

Hydraulic fracture is used in the process of extraction of shale gas in China, while there are two issues on water. Firstly, the water is in shortage. According to the public data, segregated completion and clustering fracturing in the horizontal shale gas wells need more than 10,000 tons of water per well. The population in China accounts for 24% of the world population, but the water only accounts for 6%. Meanwhile, the uneven distribution of water resources further worsens the water shortage. Thus, it is a huge challenge for shale gas development in China. For example, the water shortage in Tarim basin has delayed the development of shale gas, while in Sichuan basin, even though more water resources, it is also urgent for water supply owing to the dense population. As a serious problem in many shale gas basins in China, water shortage should be a challenge that we must overcome through developing new fracturing fluid system (Hu and Xu, 2013). Secondly, the water pollution will lead to more serious issues close to the headwaters, such as Sichuan basin. The most active shale gas events are going on in Sichuan basin. Polluted water from fracturing may flow down to the East China where the elevation is lower, which will lead to large area pollution of water resources.

4.5. Surface condition and infrastructure

The shale gas wells in USA are usually located in the plain area, avoiding the mountain areas. However, in China, the most perspective shale gas plays are in upper Yangtze area, such as Sichuan basin and eastern Chongqing, where the surface elevation varies from 1500 m to 3000 m. The relative elevation is up to 1000 m. It is a tough task to transport the huge equipment for drilling and fracturing to the well sites. The infrastructures, such as high way and road, are poorly developed due to the undulating surface and local underdeveloped economy. The oil and gas companies have to invest in developing infrastructures, along with dealing with water shortage and environmental protection (Zou et al., 2012). In addition, the transportation of produced shale gas is also a big issue in China. Different from USA, the gas pipelines are inadequate and constructed very slowly. Until July 2013, China just began to build the first shale gas pipeline from the shale gas well N201-H1. More investments are necessary for China to develop shale gas industry.

5. Conclusions

China is investing huge funding and issuing preferential policies to encourage and improve the development of shale gas industry, dealing with the huge consumption of energy. However, the special geologic features of organic-rich shale affected by depositional environments and tectonic evolution have led to new challenges. It is the first step to understand these geologic characteristics and then to find the solution. Based on large amount of data tested by ourselves and collected from published articles and theses, the geologic features of organic-rich shale, including mineral composition, organic matter richness and type, and lithology stratigraphy, were analyzed in marine, marine-continental transitional, and lacustrine environments, indicating very different characteristics from the marine shale in North America. Meanwhile, the more complex and active tectonic movements in China lead to strong deformation and erosion of organic-rich shale, the well-development of fractures and faults and higher thermal maturity and serious heterogeneity. Therefore, besides discussing the depositional model of organic-rich shale in the three environments, tectonic evolution is also a very important topic for shale gas in China. Furthermore, non-marine shale, especially the coal-bearing organic-rich shale is widely developed in China. Interlayered with coal and fine sandstone, the co-existence of shale gas, tight sand gas, and CBM has been observed in Ordos basin, Sichuan basin, and middle-lower Yangtze area. It is possible to co-produce these gases to reduce cost. More geologic analysis and discussion should be completed to support the shale gas development in China. The special geologic properties of organic-rich shale and other related problems (such as undulating surface condition, water shortage, lack of pipeline, and technology service companies) cause more difficulties to produce shale gas in China. For example, water shortage, as a serious problem in many shale gas basins in China, should be overcome through developing new fracturing fluid system. Severely undulating surface, pore development of infrastructure (e.g. roads), and lack of gas pipelines increase the difficulties to produce shale gas in China.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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