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MINERALOGY AND SHALE GAS POTENTIAL OF LOWER SILURIAN ORGANIC-RICH SHALE AT THE SOUTHEASTERN MARGIN OF SICHUAN BASIN, SOUTH CHINA

LING GUO[a,b]*, ZAIXING JIANG[c], CHAO LIANG[c]

[a] State Key Laboratory of Continental Dynamics, Northwest University, Xi'an 710069, China
[b] Department of Geology, Northwest University, Xi'an 710069, China
[c] School of Energy Resources, China University of Geosciences, Beijing 100083, China

Abstract. *Exploration for unconventional gas resources from Paleozoic formations in the Sichuan Basin in South China is just getting started. Large, potential gas reservoirs are presumed to exist in the southern and southeastern Sichuan Basin where Silurian marine organic-rich shale occurs. This paper provides geochemical and mineralogical data and other relevant information on potentially economic black shale formations of the Lower Silurian. The results show that in the shale, mineral components are dominated by clay minerals and quartz with minor amounts of plagioclase, potash feldspar, calcite and pyrite. The brittle mineral content ranges from 38 to 73% by weight (average content 56.2 wt%). In general, the Lower Silurian organic-rich shale of the Longmaxi Formation in the Sichuan Basin is highly mature, with the vitrinite reflectance between 1.6 and 3%. The shale has a high content of organic carbon, with an average of 1.8%, is tens of meters thick and of large areal extent. It can be regarded as a potential gas shale target.*

Keywords: *organic-rich shale, brittle minerals, shale gas, Lower Silurian, Longmaxi Formation, South China.*

1. Introduction

The increasing global demand for clean energy has made it imperative to explore for and exploit unconventional oil and gas resources. Shale gas is potentially one of the most important unconventional gas resources. The United States has successfully developed related business over the past

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[*] Corresponding author: e-mail *guoling@nwu.edu.cn*

decades [1, 2]. Many countries are investing in shale gas exploration, including China. Nowadays unconventional natural gas reservoirs represent an increasing focus of activity in several basins throughout China. Development of coal-bed methane, tight sand gas, and gas shale reservoirs, for example, has brought significant success in production in some of its basins. This success has not been haphazard. On the contrary, it has come about through a combination of scientific research, engineering innovation, and, in some cases, persistence and risk taking.

All of these factors have had an influence on exploiting the Lower Silurian Longmaxi gas shale in the Sichuan Basin. According to Chinese scholars, in this study the shales of the Longmaxi Formation are called "Longmaxi shale". The Longmaxi shale is an organic-rich rock of the Early Silurian stage, long recognized as a probable source rock for hydrocarbons throughout the Sichuan Basin. Nowadays the shale bed is a hot spot for shale gas exploration and exploitation. According to preliminary estimates, there is an extremely abundant shale gas reservoir with resource between 15 and 100 trillion m^3 [3, 4]. By 2012, drilling had established a core productive area, the Jiaoshiba shale gas field in Fuling, in the northwestern part of the study area (Fig. 1b), and another area in the Sichuan Basin.

Compared with commercial gas-shale plays in the United States, the Longmaxi organic-rich shale is unique in several aspects. First, the shale has undergone a complex tectonic evolvement and hydrocarbon generation history. Second, it has a relatively high thermal maturity and low total organic carbon content. Third, the Longmaxi shale has a complex mineral composition. Fourth, the shale's natural gas resource is relatively low, and is produced at greater depths.

Overall, these and other factors have presented a set of challenges to geoscientists engaged in source rock evaluation and reservoir characterization of the Longmaxi organic-rich shale. The evolving knowledge related to development of this play will likely prove valuable to future exploration and production of gas-shale reservoirs elsewhere in the Sichuan Basin.

The goal of this work is to provide detailed information on the mineralogy, geochemistry, thermal maturity and shale gas potential of Lower Silurian Longmaxi organic-rich shale, occurring in outcrops and wells at the southeastern margin of the Sichuan Basin.

2. Geological setting

The study area is located in the southeastern Sichuan Basin in South China, which is bounded by the Longmen shan tectonic belt in the west, the Daba shan tectonic belt in the northeast and the Bamian shan fault-fold belt in the east (Fig. 1a). The administrative area includes southeastern Chongqing City, northern Guizhou Province and southwestern Hubei Province (Fig. 1b).

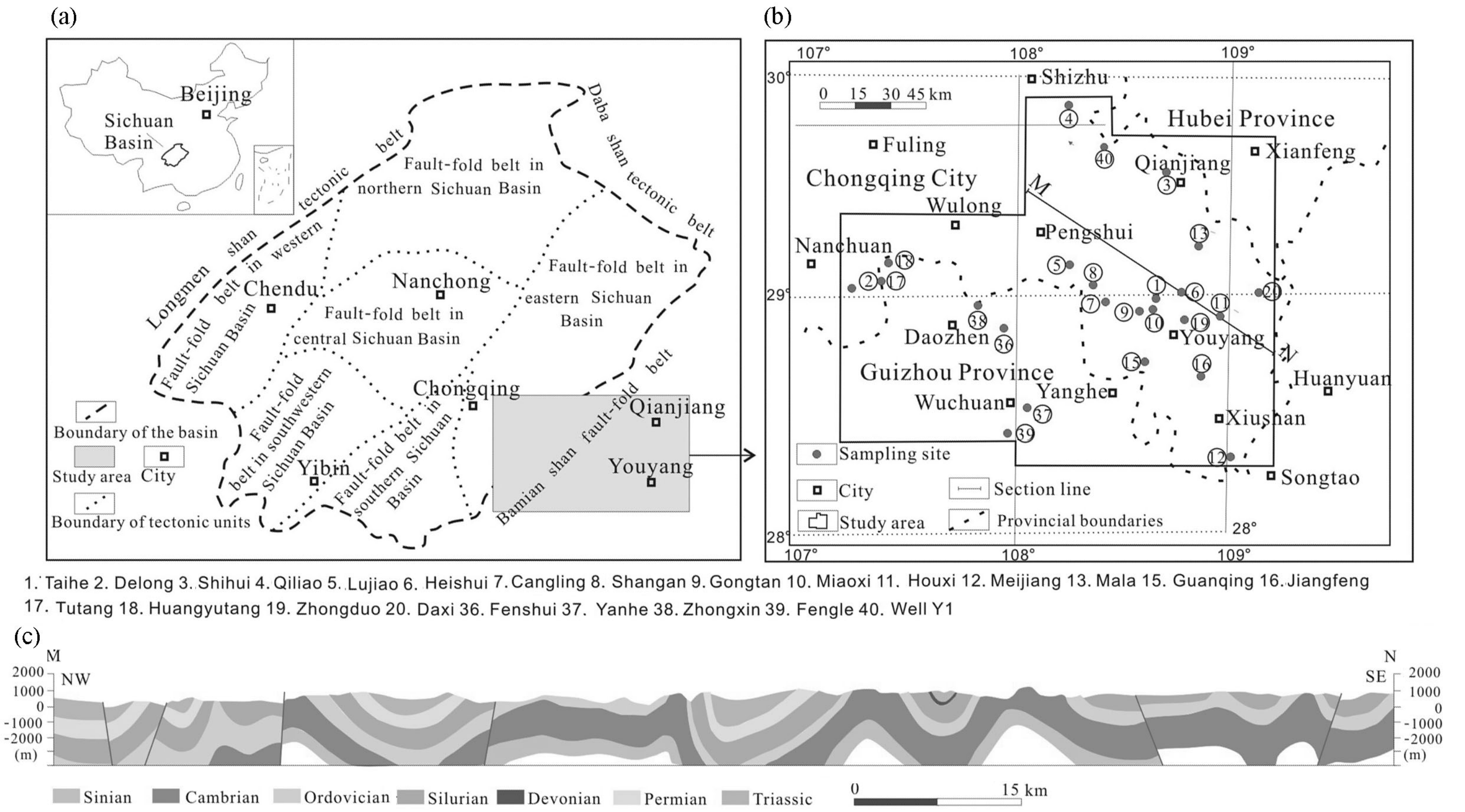

Fig. 1. Maps showing (a) location and tectonic map of the study area; (b) sampling sites distribution in the study area; (c) tectonic cross-section (position as shown in Fig. 1b) in the southeastern margin of the Sichuan Basin.

The Sichuan Basin evolved from a Sinian-Middle Triassic passive continental margin, during which thick marine carbonate and clastics interbedded with volcanics were deposited [5, 6]. In the Late Triassic, the basin was affected by closure of the Palaeo-Tethys and the subduction of oceanic crust of the Yangtze plate. The Jurassic-Quaternary was essentially a foreland basin stage with intense folding, uplift and erosion. The southeastern margin of the Sichuan Basin features relatively high uplift rates with strong tectonic compression, and the tectonic stresses of folds formed in the Cretaceous underwent relaxation or release in the Cenozoic, leading to the creation of a series of large-scale NNE-trending faults along anticlinal axes and wings that consisted of horst and graben fault systems (Fig. 1c).

The Longmaxi organic-rich shale deposited in response to the major regional flooding event of the Early Silurian, generally similar to the basal Silurian 'hot shale' in the Middle East and North Africa [6, 7]. These two black shales were mainly deposited in the anoxic deep-water shelf environment, which provided favourable conditions for the preservation of organic matter [8–10]. The Longmaxi organic-rich shale is widely distributed in the Sichuan Basin, and is an important source rock for many oil/gas fields [11, 12]. Black shale developed mostly in the middle and lower parts of the Longmaxi Formation, which are rich in organic matter and graptolites overlain by greyish green fine sandstone (Fig. 2). Generally, the gamma value shows a spike peak at the black shale in the basal Silurian, and decreases upward (Fig. 2).

3. Samples and methods

Thirty-one samples were taken systematically from the outcrops in different areas and one drilling core from well Y1, depending on the dimensions and accessibility of an individual outcrop or well. In the area with well-preserved Lower Silurian organic-rich shale outcrops, 20 samples were mostly collected in the middle part of the sections. In three small outcrops in the study area, the systematic approach was not applicable and only dark horizons were sampled (3 samples). This may result in a small bias towards more organic-rich rocks for that specific area. Eight samples from a 70 m long core from well Y1 were taken with a spacing of about 10 m as well.

3.1. Mineral composition determination by XRD

XRD analysis was performed on all the samples. X-ray powder analyses were carried out using a Bruker D8 discover x-ray diffractometer. The D8 discover employs an x-ray tube with a Cu anode as the primary x-ray beam source. Common targets used in x-ray tubes include Cu and Mo, which emit 8 keV and 14 keV x-rays with wavelengths of 1.54 Å and 0.8 Å, respectively. The readable minimum step length is 0.001° and a minimum measuring range is 50 μm. All the tests were completed at the Research Institute of Petroleum Exploration and Development, China.

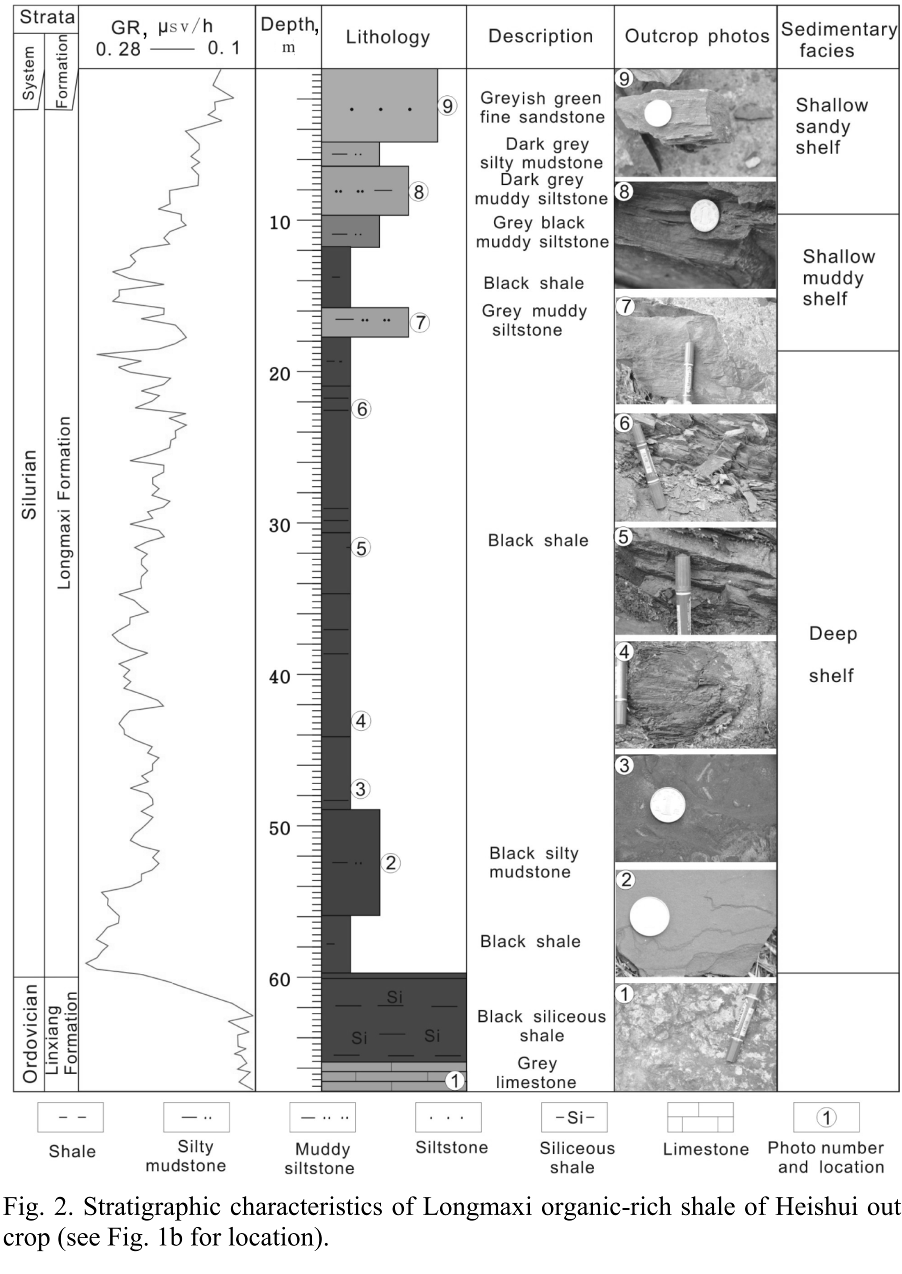

Fig. 2. Stratigraphic characteristics of Longmaxi organic-rich shale of Heishui outcrop (see Fig. 1b for location).

3.2. Geochemical analysis

Shale cores were crushed and 200 mesh samples were selected for geochemical analysis. About 100 mg of sample was placed in a crucible with 5% HCl at 80 °C to remove carbonates. The total organic carbon content (TOC) was measured using a Leco SC-632 instrument. A Rock-Eval 6 instrument was employed for pyrolysis analysis. Parameters measured included TOC; free volatile hydrocarbons, mg HC/g rock (S_1); pyrolysis hydrocarbon, mg HC/g rock (S_2); and temperature of maximum pyrolysis yield (T_{max}). Hydrogen index (HI) and production index (PI) were calculated.

A Laborlux12pol fluorescence microscope (Leitz, Germany) with oil-immersion 50× objectives and an MPV-3 microscope photometer instrument determined the maturity of organic matter in a sample weighing about 70 g. All the tests were completed at the Research Institute of Petroleum Exploraion and Development, China.

4. Results and discussion

4.1. Mineral content

XRD phase identification was performed for 31 selected black shale samples and revealed the presence of the same major minerals in all of them: quartz, clay minerals, feldspars, carbonates and pyrite. Twenty-three of the 31 samples investigated represent the outcrops of the Lower Silurian Longmaxi Formation, whereas eight are from the cores collected form well Y1. Clay minerals predominate in all samples, ranging from 27 to 62% (Table 1 and Fig. 3), followed by quartz of similar amounts and lower contributions of carbonate, feldspars and pyrite. Clay minerals are mainly represented by illite, mixed illite/smectite and chlorite of varying amounts, with illite being the major one in all samples. Feldspars were identified as potash feldspar and plagioclase. Each of these two feldspars can be dominant, but in general, plagioclase is slightly more abundant than potash feldspar (Table 1).

Quantitative analyses also showed that clay minerals, with an average content of 43%, are the most abundant minerals in the majority of samples, followed by quartz which, however, sometimes surpasses them in quantity (Fig. 3 and Table 1). The quartz content varies between about 10 and 62% with an average value of about 38%. The feldspars content ranges from about 3 to 25% with an average value of 10.3%. Carbonate was identified as calcite and dolomite. The content of calcite, which is present in 24 samples, varies between 0 and 54% with an average content of 5.2%. The content of dolomite, which is present in only 13 samples, is from 0 to 19% with an average content of 2.5%. The content of pyrite, which was mainly detected in core samples, varies between 0 and 4.9% with an average content of 0.8% (Table 1). Quartz, feldspars and carbonates are regarded as brittle minerals which have an important effect on the shale fragility [6, 13]. The brittle mineral content in Longmaxi organic-rich shale ranges from 38 to 73% by weight, with an average content of 56.2 wt%.

Table 1. Mineral composition of selected Longmaxi organic-rich shale samples, %

Sample No.	Chlorite	Illite	I/S	%S	TC	Quartz	PF	Plagioclase	Calcite	Dolomite	Pyrite
TH-1	11.0	60.0	29.0	5.0	35.0	45.0	4.0	12.0	4.0	0.0	0.0
DL-2	14.0	66.0	20.0	10.0	270	25.0	1.0	3.0	25.0	19.0	0.0
SH-3	3.0	62.0	35.0	15.0	27.0	62.0	5.0	4.0	2.0	0.0	0.0
QL-4	2.0	60.0	38.0	30.0	41.0	47.0	3.0	9.0	0.0	0.0	0.0
LJ-5	15.0	52.0	33.0	10.0	43.0	40.0	2.0	13.0	2.0	0.0	0.0
HS-6	23.0	53.0	24.0	10.0	54.0	37.0	2.0	7.0	0.0	0.0	0.0
CL-7	2.0	11.0	87.0	50.0	30.0	10.0	0.0	6.0	54.0	0.0	0.0
SG-8	19.0	59.0	22.0	10.0	49.0	34.0	2.0	7.0	5.0	3.0	0.0
GT-9	18.0	54.0	28.0	10.0	35.0	41.0	6.0	13.0	5.0	0.0	0.0
MX-10	21.0	61.0	18.0	10.0	55.0	37.0	1.0	7.0	0.0	0.0	0.0
HX-11	14.0	61.0	25.0	10.0	28.0	43.0	5.0	20.0	4.0	0.0	0.0
MJ-12	22.0	61.0	17.0	10.0	52.0	33.0	1.0	7.0	7.0	0.0	0.0
ML-13	16.0	59.0	25.0	10.0	54.0	32.0	3.0	6.0	5.0	0.0	0.0
GQ-15	11.0	68.0	21.0	10.0	41.0	41.0	2.0	5.0	3.0	8.0	0.0
JF-16	16.0	60.0	24.0	15.0	28.0	40.0	10.0	15.0	7.0	0.0	0.0
TT-17	18.0	58.0	24.0	10.0	41.0	41.0	3.0	5.0	3.0	7.0	0.0
HYT-18	2.0	81.0	17.0	5.0	46.0	51.0	0.0	3.0	0.0	0.0	0.0
ZD-19	17.0	52.0	31.0	10.0	62.0	25.0	3.0	9.0	1.0	0.0	0.0
DX-20	15.0	44.0	41.0	10.0	43.0	45.0	4.0	1.0	7.0	0.0	0.0
FS-36	10.0	44.0	46.0	15.0	42.0	42.0	1.0	7.0	5.0	2.0	1.0
YH-37	18.0	41.0	41.0	10.0	58.0	33.0	0.0	4.0	5.0	0.0	0.0
ZX-38	9.0	50.0	41.0	10.0	46.0	44.0	1.0	5.0	0.0	3.0	1.0
FL-39	19.0	41.0	40.0	10.0	56.0	36.0	1.0	7.0	0.0	0.0	0.0
Y-40	23.0	77.0	0.0	0.0	38.9	37.9	1.8	11.0	1.8	5.8	2.8
Y-41	18.0	82.0	0.0	0.0	42.4	39.4	1.6	9.6	2.2	2.4	2.4
Y-42	16.0	84.0	0.0	0.0	38.2	38.0	2.4	12.9	0.7	5.1	2.7
Y-43	18.0	82.0	0.0	0.0	39.9	41.5	1.3	10.3	1.3	3.1	2.6
Y-44	13.0	87.0	0.0	0.0	41.1	37.5	1.8	8.7	2.1	3.9	4.9
Y-45	14.0	86.0	0.0	0.0	38.3	40.8	0.6	7.0	3.5	6.8	3.0
Y-46	11.0	89.0	0.0	0.0	41.6	37.1	1.1	7.4	4.1	5.1	3.6
Y-47	29.0	71.0	0.0	0.0	58.7	32.8	0.4	6.6	0.0	0.0	1.5

I/S – mixed illite/smectite, %S – proportion of mixed layer, TC – total clay mineral content, PF – potash feldspar.

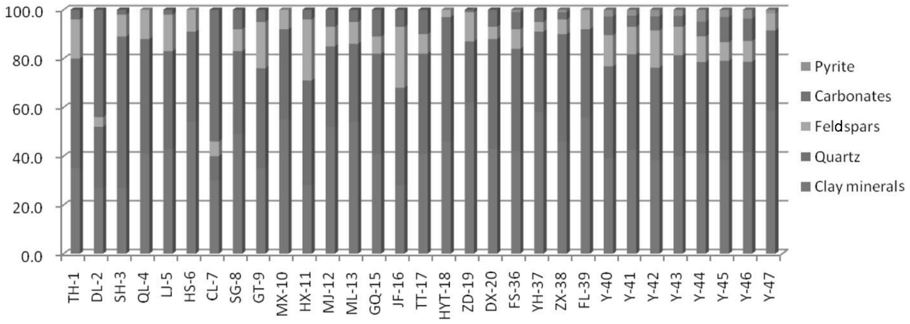

Fig. 3. Bulk mineralogy of selected Longmaxi organic-rich shale samples from the study area according to XRD data (see Fig. 1b for sample location).

4.2. TOC and Rock-Eval pyrolysis

Total organic carbon content (TOC, wt%) is used to determine the amount of organic matter and evaluate the hydrocarbon generative potential of shale. The Longmaxi organic-rich shale has high TOC contents ranging from 0.12 to 6.16%, with an average content of 1.75% (Table 2), suggesting relatively good to excellent source rock generative potential [14]. The amount of hydroarbon (S_2) generated during pyrolysis is a useful parameter to evaluate the generative potential of source rocks [14]. The shale samples have pyrolysis S_2 yields in the range of 0.01 to 0.32 mg HC/g rock (Table 2), which meet the accepted standards for a source with fair petroleum source rock generative potential. Hydrogen and production indices of the samples were calculated. The hydrogen index ranges from 0.33 to 18.07 HC/g TOC mg, and production index is between 0.19 and 0.52 (Table 2). In addition, T_{max} value representing the temperature at which the S_2 peak is at its maximum is also determined [15]. The shale samples have T_{max} values in the range of 377–586 °C, which mainly reflect the trend of thermal maturity, but may also be influenced by kerogen type [16]. Most of those samples have HI values < 0 mg HC/g TOC. The maturity determined by R_o and T_{max} suggests that the majority of the samples lie within the mature to overmature zone of hydrcarbon generation [15], which accords with findings of Liang et al. and Pu et al. [6, 17].

Production index ($PI = S_1/S_1 + S_2$) is an indicator of the amount of volatile "free" hydrocarbons that is related to the presence of migrated oil or the amount of redistributed liquid hydrocarbons (generated by the cracking of kerogen) by primary migration. The vast majority of the samples show anomalously high PI values (0.19–0.52), suggesting the presence of redistributed hydrocarbons, or migrated oil, in most of the non-contaminated samples. The anomalously high PI (> 0.2) in non-contaminated, immature samples indicates the presence of allochthonous hydrocarbons.

Table 2. Bulk geochemical results for Longmaxi organic-rich shale samples from TOC/Rock-Eval analysis using calculated parameters and vitrinite reflectance (%R_o)

Sample No.	TOC, wt%	Rock-Eval pyrolysis							R_o, %
		S_1, mg/g	S_2, mg/g	T_{max}, °C	I_{HC}, mg/g	CP, %	HI	PI	
DL-2	0.27	0.025	0.029	386.000	9.191	0.005	10.662	0.463	2.820
SH-3	5.53	0.035	0.048	584.000	0.633	0.007	0.868	0.422	2.540
QL-4	2.00	0.027	0.025	430.000	1.350	0.005	1.250	0.519	2.570
HS-6	0.26	0.013	0.024	382.000	4.924	0.003	9.091	0.351	2.620
CL-7	1.76	0.076	0.318	555.000	4.318	0.033	18.068	0.193	2.620
SG-8	1.09	0.032	0.032	381.000	2.936	0.005	2.936	0.500	2.440
MX-10	0.12	0.012	0.014	466.000	10.435	0.002	12.174	0.462	3.090
HX-11	0.43	0.020	0.028	576.000	4.651	0.004	6.512	0.417	2.860
JF-16	0.34	0.048	0.058	583.000	14.159	0.009	17.109	0.453	–
TT-17	0.83	0.010	0.021	543.000	1.203	0.003	2.527	0.323	–
HYT-18	5.53	0.017	0.018	381.000	0.307	0.003	0.325	0.486	3.680
FS-36	1.35	0.039	0.046	377.000	2.889	0.007	3.407	0.459	–
YH-37	0.25	0.015	0.032	398.000	5.906	0.004	12.598	0.319	–
ZX-38	6.16	0.037	0.078	586.000	0.601	0.010	1.266	0.322	2.530
FL-39	0.40	0.010	0.035	516.000	2.532	0.004	8.861	0.222	1.600

TOC – total organic carbon, wt%;
S_1 – free volatile hydrocarbons thermally flushed from a rock sample at 300 °C, mg HC/g rock;
S_2 – pyrolysis HC detected from 300 °C to 600 °C, mg HC/g rock;
T_{max} – temperature at maximum of S_2 peak;
I_{HC} – hydrocarbon index, mg/g;
CP – effective carbon, %;
HI – hydrogen index = $S_2 \times 100/\text{TOC}$, mg HC/g TOC;
PI – production index = $S_1/(S_1 + S_2)$.

4.3. Thermal maturity

Thermal maturity of the organic matter in the Longmaxi organic-rich shale was evaluated based on vitrinite reflectance (%R_o) and Rock-Eval pyrolysis T_{max} values. Vitrinite reflectance as a parameter is widely accepted and considered reliable by many authors and exploration geologists for determining the thermal maturity of source rocks. Vitrinite reflectance values indicate mature to overmature organic matter in the catagenesis stage (1.61–3.7%; Table 2), suggesting oil-generation to gas-generation window. Table 2 presents T_{max} values of pyrolysis for all samples as well. T_{max} value can also be used as a maturity indicator, though it may vary significantly depending on kerogen type [14]. Pyrolysis T_{max} values ranging from 377 to 586 °C indicate generally mature to overmature organic matter [16]. This is in good agreement with the mean vitrinite reflectance (%R_o) values (Table 2) and high fluorescent organic matter contents determined under fluorescent light excitation (Fig. 4).

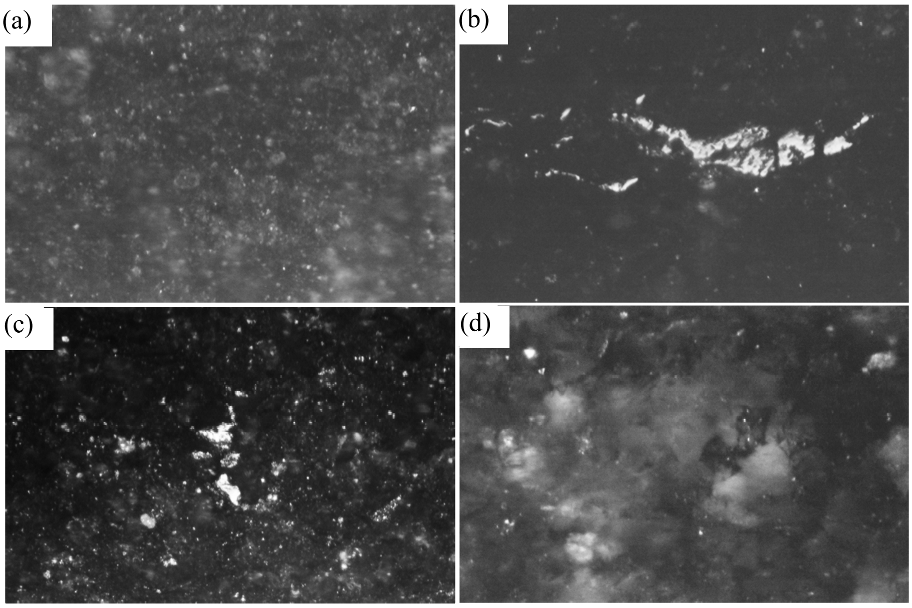

Fig. 4. Photomicrographs of kerogen in the Longmaxi organic-rich shale under plane polarized incident fluorescence, sample No. TT-17: (a) high bitumen staining associated with clay minerals, sample No. LJ-5; (b) blocky bitumen fluorescing bright yellow, sample No. Y-12; (c) pyrolysis bitumen suggesting mature organic matter within shale; (d) distinct orange fluorescence intensities corresponding to amorphous organic matter assemblages, sample No. JF-16.

4.4. Gas generative potential

The geochemical and kerogen microscopy results indicate that the Longmaxi organic-rich shale has a very good gas generative potential. There is a good agreement between Rock-Eval pyrolysis data, TOC and vitrinite reflectance values obtained in this work and the corresponding values reported earlier by Liang et al. and Pu et al. [6, 17]. In this study, the kerogen of Longmaxi organic-rich shale is predominantly a mixture of Types I and III. Shales, which mostly contain Type I and III kerogens and are characterized by high TOC with an average content of 1.75% and a high amount of bright yellow bitumen, can generate oil/gas. Shales having average R_o values higher than 2% mainly generate gas. In addition, shales that contain vitrinitic Type III kerogen would be expected to generate gas with HI < 200 mg HC/g TOC. Considering thermal maturity and generative potential, the Longmaxi organic-rich shale in the southeastern Sichuan Basin is a source rock of mainly gas generating potential. This is supported by three lines of evidence: 1) microscopic observations of samples enriched in pyrolysis bitumen (Fig. 4c); 2) microscopic observations of high levels of bitumen staining (Fig. 4a–d) attributed to higher thermal maturity (1.6–3.7% R_o); and 3) relatively high TOC with an average content of 1.75%.

Analyses of cores show that the absorbed gas content of Longmaxi organic-rich shale is approximately 1.5–2.0 m^3/t, whereas in outcrop samples the corresponding value is 2 m^3/t [6]. Studies show that the gas content has a positive correlation with the TOC content, which can be explained by the fact that organic matter has a strong adsorption potential for gas [6]. Large volumes of shale gas are adsorbed on the inner surface of kerogen within the organic-rich shale, and hence the high TOC content indicates a large shale gas volume and adsorption capacity in the Longmaxi shale.

4.5. Gas shale potential and comparison to US gas shales

As discussed by Curtis [18] and Jarvie et al. [19], factors controlling the potential of a gas shale system include thickness and lateral extent, total organic carbon content, porosity, and mineral composition, which greatly influence frangibility. During increasing thermal maturation, conversion of kerogen to petroleum and finally dry gas results in the formation of a carbon-rich residue and secondary porosity, which affects gas storage capacity. Porosity may increase within the dry-gas window (> 1.4% R_o) by about 4 to 5 vol% due to hydrocarbon generation and expulsion [19].

The results obtained in this study on Longmaxi organic-rich shale were compared to those for the well-known US gas shales. In comparison, the shales' bulk mineralogy, brittleness and average thickness were taken into account.

As established by Curtis, porosity and permeability in US shale reservoirs are quite low [18]. Shale gas exploration and development in the United States has demonstrated that the fissure system is extremely important in exploiting it [19]. Curtis and Jarvie et al. have suggested that mineral composition is the controlling factor for rock fragility, and the more abundant the brittle minerals, such as quartz and carbonate, are, the higher the brittleness of shale is [18, 19]. The fissure system may be easily formed under the effect of geostress. Figure 5a visualizes values for specific minerals of Chinese Longmaxi organic-rich shale, and Figure 5b illustrates values for specific minerals of US commercial gas shales, including Bossier shale, Woodford/ Barnett shale in west Texas, Ohio shale and Barnett siliceous shale. In Longmaxi shale, total quartz, feldspars and pyrite contents range from 37 to 70% by weight, excluding two negative excursions. The content of clay minerals is approximately 27 to 62%, which is slightly lower than total quartz, feldspars and pyrite contents, the carbonate content is between 0 and 14%, except for two values. In the United States, gas shale exploitation is carried out in two major regions, Ohio and west Texas. Total quartz, feldspars and pyrite contents of these shales are lower than 50%, the carbonate content ranges from 5 to 90% by weight. In general, in Ohio and Woodford/Barnett (west Texas) shales the carbonate content is lower than 20%; total quartz, feldspars and pyrite contents vary between 25 and 80%, while the total clay minerals content is between 15 and 65%. The clay content in Barnett shale is generally lower than 50%, and total quartz, feldspars and pyrite contents are higher than 40%. As mentioned above, the mineral distribution in the Longmaxi organic-rich shale is quite similar to the Ohio shale's. The Ohio shale was the first to provide commercial gas for the United States and accounted for the majority of the country's gas production until 1994 [18]. Depending on mineral composition, the brittleness of Longmaxi organic-rich shale is generally quite similar to that of Ohio shale (Fig. 5). Also, conditions for shale gas accumulation for the Longmaxi shale are comparable to those for the Ohio shale.

As found by Curtis, fractures are an effective reservoir in gas shale [18]. Fracture development mainly depends on internal causes, such as shale brittleness (brittle mineral content), and external causes, including crustal stress, temperature and fluid pressure. In case of US Ohio and west Texas shales, quartz content divided by the sum of quartz, carbonates and clay minerals contents reflects shale brittleness as the shales developed in these areas are mainly marine sediments and quartz is their dominant brittle mineral [22]. The Longmaxi organic-rich shale also developed in a marine deep shelf [10]. In the study area, shale brittleness described as above varies between about 0.11 and 0.68 with an average value of about 0.43 (Fig. 6). Organic-rich shale samples with brittleness higher than 0.40 account for more than 70% of the selected samples, suggesting that natural fractures probably developed well and artificial fractures formed easily. Actually, natural fractures developed very well in the Longmaxi organic-rich shale as shown in Figure 7.

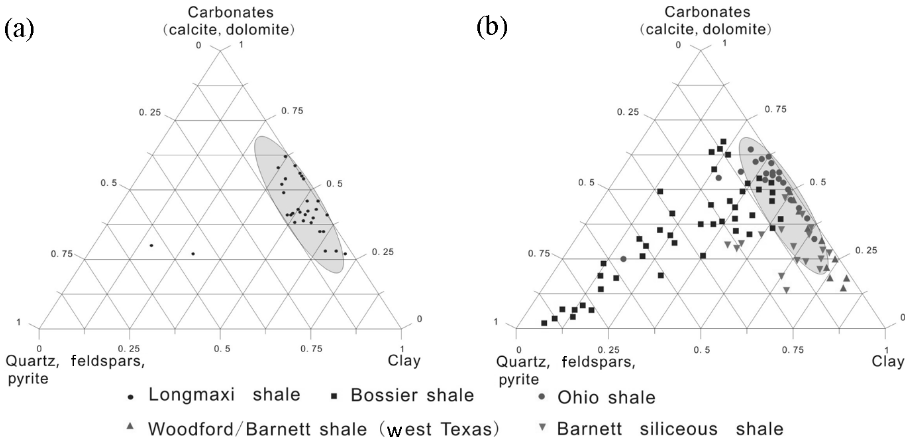

Fig. 5. Ternary diagram of mineral composition of shale reservoir: a) ternary diagram showing Longmaxi organic-rich shale mineralogical data from X-ray diffraction analyses; b) mineral composition of US Bossier shale, Woodford/Barnett shale, Ohio shale and Barnett siliceous shale, with their commercial shale gas output (data from [20, 21]).

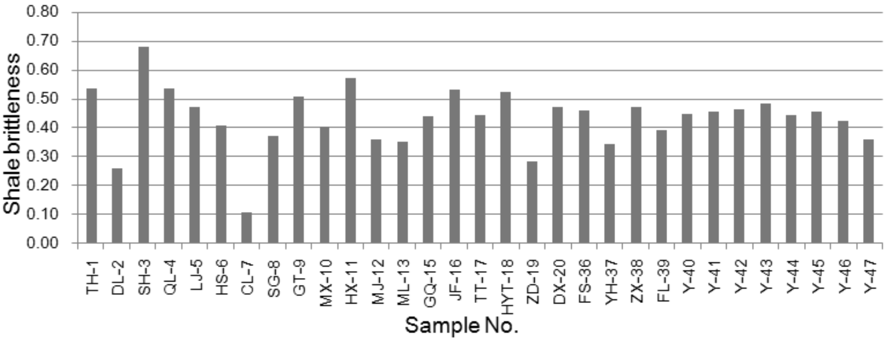

Fig. 6. Brittleness of Longmaxi organic-rich shale samples in the southeastern Sichuan Basin.

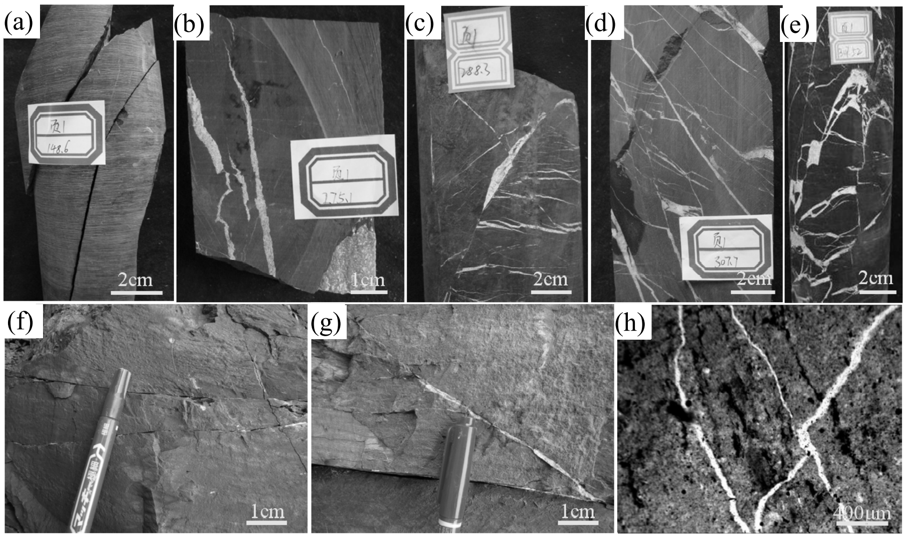

Fig. 7. Pictures showing natural fractures developed in Longmaxi organic-rich shale: (a) black shale showing high angle fractures, well Y1; (b–e) black shale showing fractures filled with quartz, well Y1; (f, g) outcrops exhibiting natural fractures partly filled with carbonates, Wulong County; (h) slice of shale showing fractures which are filled or partly filled with quartz, well Y1.

The dominant facies in the early Longmaxi stage are deep shelf and shallow muddy shelf (Fig. 8a). These two facies were deposited in the middle and northern parts of the study area. The bathyal plain and the shallow sandy shelf were located only in the northeastern and southern parts of the study area. Generally, the facies are distributed symmetrically and water depth reaches its maximum in the northern part of the study area, decreasing towards the south. Figure 8b visualizes values of the thickness of Longmaxi organic-rich shale in the southeastern Sichuan Basin. The thickness of Longmaxi organic-rich shale is maximum, 70 m, in well Y1 located in the northern part of the study area, and minimum, 4 m, in Meijiang in its southern part.

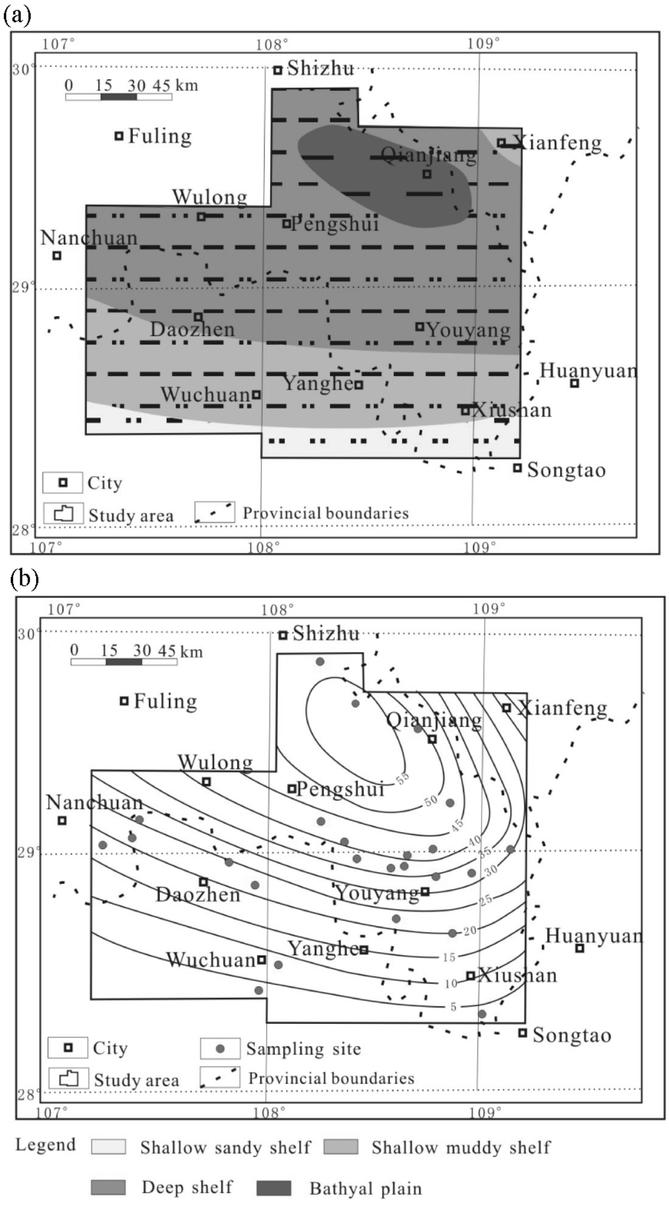

Fig. 8. (a) Sedimentary facies map of early Longmaxi stage (after [10]); (b) contour map showing thickness of Longmaxi organic-rich shale.

Shale gas is a self-generated and self-stored gas resource, while gas is mainly accumulated in shale [18]. As described above, the Longmaxi organic-rich shale is a high quality source rock (high TOC content, relatively high R_o, relatively high absorbed gas content and great thickness of black shale) and, no doubt, has a high gas generation capacity. High brittle mineral content, which most certainly favours the development of fractures, together with good porosity and permeability suggest that the Longmaxi organic-rich shale has mainly good reservoir capacity [6]. Conducted by Chinese Sinopec Corp., the drilling of horizontal fracturing well JY1HF located in Fuling about 30 km from the northwestern part of the study area yielded 20.3×10^4 m^3/d of gas in 2012 [23]. Drilling of other horizontal fracturing wells has also given good results [24]. The Longmaxi organic-rich shale is well-developed and widely distributed in the study area and, hence, shale gas exploration in this region is a capacious undertaking. According to preliminary forecasts, the Longmaxi organic-rich shale gas resources may reach 0.27×10^{12} to 2.03×10^{12} m^3, with an expected value of 0.93×10^{12} m^3 in this area [25].

5. Conclusions

Geochemical results reveal that the Longmaxi organic-rich shale in the southeastern Sichuan Basin in South China is generally of very good gas-generative potential. The shale has a high organic matter content with a total organic carbon content (TOC) of up to 6 wt%, while the high total content of organic matter is mainly due to the good preservation of the matter.

Values of vitrinite reflectance (1.6–3.7% R_o) and T_{max} (377–586 °C), and microscopic characteristics of kerogen indicate that the Longmaxi organic-rich shale has entered the mature to overmature gas window. Due to its maturity character, the shale in the southeastern Sichuan Basin is considered to have generated significant amounts of gas.

The Longmaxi shale is dominated by clay minerals and quartz, followed by feldspars, carbonates and pyrite. The average brittle mineral content in the shale is 56.2%. The shale in the study area is especially regarded as a potential target for shale gas exploration. Favourable factors for shale gas accumulation are: 1) high TOC content and high maturity of shale; 2) great thickness and large areal extent of shale; 3) high rock brittleness with an average value of 0.43; and 4) stable anoxic deep-water sedimentary environment.

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REFERENCES

1. Bowker, K. A. Barnett Shale gas production, Fort Worth Basin: issues and discussion. *AAPG Bull.*, 2007, **91**(4), 523–533.
2. Chen, S., Zhu, Y., Qin, Y., Wang, H., Liu, H., Fang, J. Reservoir evaluation of the Lower Silurian Longmaxi Formation shale gas in the southern Sichuan Basin of China. *Mar. Petrol. Geol.*, 2014, **57**, 619–630.
3. Zhang, J. C., Nie, H. K., Xu, B., Jiang, S. L., Zhang, P. X., Wang, Z. Y. Geological condition of shale gas accumulation in Sichuan Basin. *Natural Gas Industry*, 2008, **28**(2), 151–156 (in Chinese with English abstract).
4. Zou, C. N., Dong, D. Z., Wang, S. J., Li, J, Li, X. J, Wang, Y., Li, D., Cheng, K. M. Geological characteristics and resource potential of shale gas in China. *Petrol. Explor. Develop.*, 2010, **37**(6), 641–653.
5. Xu, S. L., Chen, H. D., Chen, A., Lin, L. B., Li, J. W., Yang, J. B. Source rock characteristics of marine strata, Sichuan Basin. *Journal of Jilin University, Earth Science Edition*, 2011, **41**(2), 343–350 (in Chinese with English abstract).
6. Liang, C., Jiang, Z. X., Zhang, C., Guo, L., Yang, Y. T., Li, J. The shale characteristics and shale gas exploration prospects of the Lower Silurian Longmaxi shale, Sichuan Basin, South China. *J. Natural Gas Sci. Eng.*, 2014, **21**, 636–648.
7. Dardour, A. M., Boote, D. R. D., Baird, A. W. Stratigraphic controls on Palaeozoic petroleum systems, Ghadames basin, Libya. *J. Petrol. Geol.*, 2004, **27**(2), 141–162.
8. Galeazzi, S., Point, O., Haddadi, N., Mather, J., Druesne, D. Regional geology and petroleum systems of the Illizi-Berkine area of the Algerian Saharan Platform: an overview. *Mar. Petrol. Geol.*, 2010, **27**(1), 143–178.
9. Liang, C., Jiang, Z. X., Yang, Y. T., Wei, X. J. Shale lithofacies and reservoir space of the Wufeng–Longmaxi Formation, Sichuan Basin. *Petrol. Explor. Develop.*, 2012, **39**(6), 691–698 (in Chinese with English abstract).
10. Jiang, Z. X., Guo, L., Liang, C. Lithofacies and sedimentary characteristics of the Silurian Longmaxi Shale in the southeastern Sichuan Basin, China. *Journal of Palaeogeography*, 2013, **2**(3), 238–251.
11. Liang, D. G., Guo, T. L., Bian, L. Z., Chen, J., Zhao, Z. Some progresses on studies of hydrocarbon generation and accumulation in marine sedimentary regions, Southern China (Part 3): Controlling factors on the sedimentary facies and development of Palaeozoic marine source rocks. *Marine Origin Petroleum Geology*, 2009, **14**(2), 1–19 (in Chinese with English abstract).
12. Guo, L., Jiang, Z. X., Zhang, J. C., Li, Y. X. Paleoenvironment of Lower Silurian black shale and its significance to the potential of shale gas, southeast

of Chongqing, China. *Energy Exploration & Exploitation*, 2011, **29**(5), 597–616.

13. Dong, D. Z., Cheng, K. M., Wang, Y. M., Li, X. J., Wang, S. J., Huang, J. L. Forming conditions and characteristics of shale gas in the Lower Paleozoic of the Upper Yangtze region, China. *Oil & Gas Geology*, 2010, **31**(3), 288–299 (in Chinese with English abstract).
14. Peters, K. E. Guidelines for evaluating petroleum source rock using programmed pyrolysis. *AAPG Bull.*, 1986, **70**(3), 318–329.
15. Espitalie, J., Deroo, G., Marquis, F. Rock-Eval pyrolysis and its applications. *Revue de l'Institut Français du Pétrole*, 1985, **40**(5), 563–579.
16. Sun, T., Wang, C. S., Li, Y. L., Wang, L. C., He, J. L. Geochemical investigation of lacustrine oil shale in the Lunpola Basin (Tibet): implications for paleoenvironment and paleoclimate. *Oil Shale*, 2013, **30**(2), 101–116.
17. Pu, B. L., Jiang, Y. L., Wang, Y., Bao, S. J., Liu, X. J. Reservoir forming conditions and favorable exploration zones of shale gas in Lower Silurian Longmaxi Formation of Sichuan Basin. *Acta Petrolei Sinica*, 2010, **31**(2), 225–230 (in Chinese with English abstract).
18. Curtis, J. B. Fractured shale-gas systems. *AAPG Bull.*, 2002, **86**(11), 1921–1938.
19. Jarvie, D. M., Hill, R. J., Ruble, T. E., Pollastro, R. M. Unconventional shale-gas systems: The Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. *AAPG Bull.*, 2007, **91**(4), 475–499.
20. Li, X. J., Lu, Z. G., Dong, D. Z., Cheng, K. M. Geologic controls on accumulation of shale gas in North America. *Natural Gas Industry*, 2009, **29**(5), 27–32 (in Chinese with English abstract).
21. Hammes, U., Hamlin, H. S., Ewing, T. E. Geologic analysis of the Upper Jurassic Haynesville Shale in east Texas and west Louisiana. *AAPG Bull.*, 2011, **95**(10), 1643–1666.
22. Li, J. Y. Analysis on mineral components and frangibility of shales in Dongying depression. *Acta Sedimentologica Sinica*, 2013, **31**(4), 616–620 (in Chinese with English abstract).
23. Zheng, H. R., Gao, B., Peng, Y. M., Nie, H. K., Yang, F. R. Sedimentary evolution and shale gas exploration direction of the Lower Silurian in Middle-Upper Yangtze area. *Journal of Palaeogeography*, 2013, **15**(5), 645–656 (in Chinese with English abstract).
24. Guo, T. L., Zhang, H. R. Formation and enrichment mode of Jiaoshiba shale gas field, Sichuan Basin. *Petrol. Explor. Develop.*, 2014, **41**(1), 28–36 (in Chinese with English abstract).
25. Han, S., Zhang, J., Li, Y., Horsfield, B., Tang, X., Jiang, W., Chen, Q. Evaluation of Lower Cambrian shale in northern Guizhou province, South China: Implications for shale gas potential. *Energ. Fuel.*, 2013, **27**(6), 2933–2941.

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